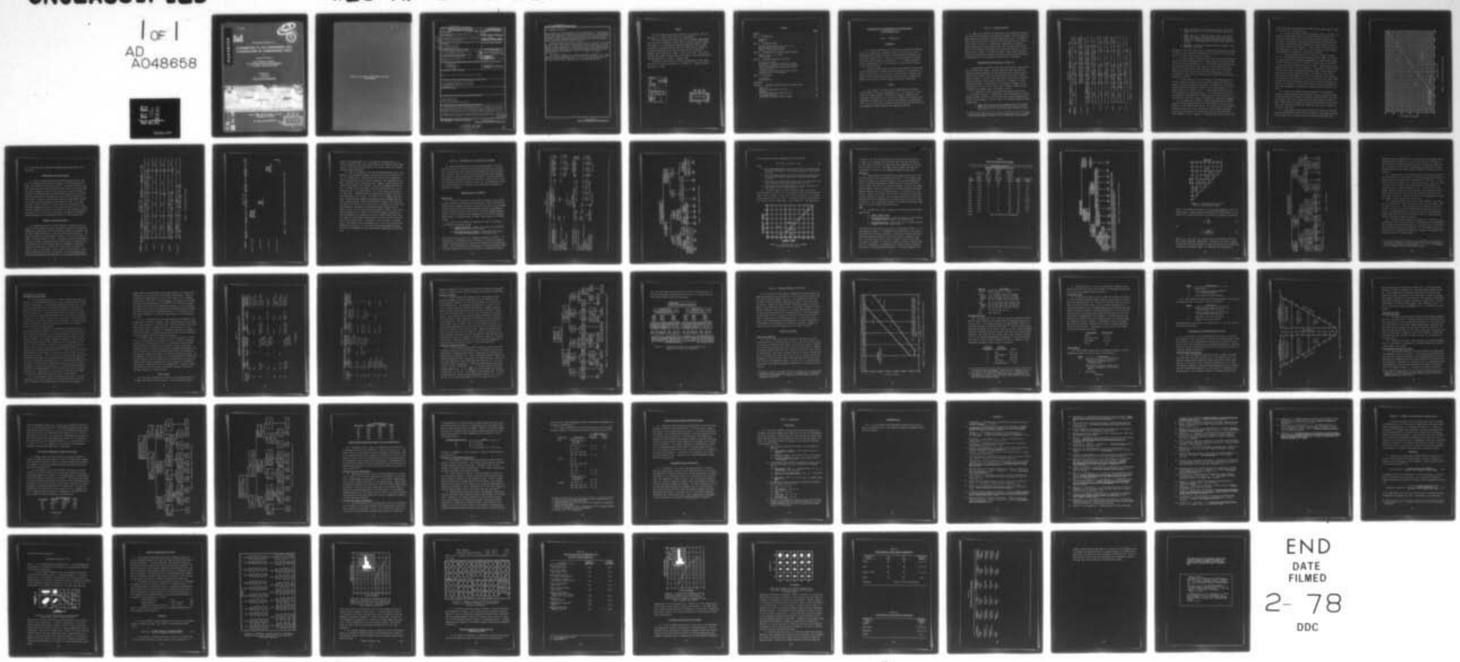
AD-A048 658 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 8/13
CONTRIBUTION TO THE ENGINEERING SOIL CLASSIFICATION OF COHESION--ETC(U)
NOV 77 M M AL-HUSSAINI

UNCLASSIFIED WES-MP-S-77-21 NL

1 OF 1
AD
A048658



END
DATE
FILMED
2-78
DDC

MISCELLANEOUS PAPER S-77-21

CONTRIBUTION TO THE ENGINEERING SOIL CLASSIFICATION OF COHESIONLESS SOILS

by

Mosaid M. Al-Hussaini

Soils and Pavements Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

November 1977

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Project No. 4A161102AT22

Destroy this report when no longer needed. Do not return it to the originator.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper S-77-21 ✓	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 CONTRIBUTION TO THE ENGINEERING SOIL CLASSIFICATION OF COHESIONLESS SOILS.		5. TYPE OF REPORT & PERIOD COVERED Final report. Sep 75 - Dec 76, 6. ~~PERFORMING ORG. REPORT NUMBER~~
7. AUTHOR(s) 10 Mosaid M./Al-Hussaini		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 ~~Project No~~ 4A161102AT22
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE 11 Nov[redacted] 1977 13. NUMBER OF PAGES 61
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 12 65p.		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

14 WES-MP-S-77-21

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cohesionless soils
Soil classification
Unified Soil Classification System

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of a soil classification system is to provide a concise and systematic method of identifying materials in order to characterize their probable engineering behavior. Soil classification permits comparisons between materials and provides a basis for accumulating experience gained with soils.

→This report is a state-of-the-art examination of existing soil classification systems with emphasis on classification of cohesionless soils. The purpose

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

038 100

LB

20. ABSTRACT (Continued).

of the report is to note and suggest possible improvements to the Unified Soil Classification System currently used by the Corps of Engineers. Characteristics of soil types pertaining to roads and airfields and soil stabilization are also considered. Criteria for differentiating between coarse-grained soil groups which have diverse engineering properties, but which are not fully described in other classification systems, are also proposed.

Boundaries between clean gravels or sands, gravels or sands with some fines, gravels or sands with fines, and fine-grained soils are suggested as 5, 20, and 50 percent fines, respectively. Coarse-grained soils are also classified with respect to their coefficient of uniformity and coefficient of curvature as well graded and poorly graded, with the poorly graded further separated into narrow (i.e. uniform) and gap gradations. Criteria to separate each group are presented.

The Atterberg fraction (i.e., material passing No. 40 (425-μm) U. S. standard series sieve) is separated into categories of low, intermediate, high, very high, and extremely high liquid limit. It is also proposed that the No. 10 (2.00-mm) sieve be used to separate gravel- from sand-size particles.

PREFACE

The study reported herein was sponsored by the Office, Chief of Engineers, U. S. Army, under Project No. 4A161102AT22.

The study was conducted during the period September 1975-December 1976 in the Soil Mechanics Division (SMD), Soils and Pavements Laboratory (S&PL), U. S. Army Engineer Waterways Experiment Station (WES). The study was conducted and the report was authored by Dr. Mosaid M. Al-Hussaini, SMD, under the general direction of Mr. Clifford L. McAnear, Chief, SMD, and Mr. James P. Sale, Chief, S&PL. The section dealing with chemical stabilization with respect to soil classification was contributed by Dr. Frank C. Townsend, SMD.

Directors of WES during the study and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONTRIBUTION TO THE ENGINEERING SOIL CLASSIFICATION OF COHESIONLESS SOILS

PART I: INTRODUCTION

Background

1. To describe and discuss soils concisely, geotechnical engineers must have a classification system by which a particular soil can be distinguished and grouped according to characteristics determined from appropriate standard tests. Once soils have been grouped into classes possessing similar engineering properties (i.e., strength, compressibility, permeability, etc.), an indication of their expected behavior can be rapidly obtained.

2. Currently, most popular classification systems for cohesionless soils are based solely on grain-size distribution; no consideration is given to grain shape or to the nature of fines present. However, this approach may not necessarily provide correlation with the engineering behavior since soils of similar geometry can behave differently.

Purpose

3. This report is a state-of-the-art examination of existing classification systems for cohesionless soils. Its purpose is to describe and compare various classification systems, indicating their advantages and limitations, in an effort to identify the system or combinations of systems that best reflects cohesionless soil characteristics. Also, it will seek to indicate where existing classifications can be extended to estimate physical and engineering behavior.

PART II: LITERATURE REVIEW

4. Many soil classification systems have been proposed for different fields of specialization and different problems. Most of these systems are based on arbitrarily assigned grain-size limits. The development of each classification system has been influenced by such factors as the field of study (e.g., agriculture, engineering, or geology), previous work done, the prevailing system used, testing devices available for the analysis, and simplicity in presenting results, as well as other factors. Since it is beyond the scope of this study to discuss every soil classification system, only those related to the development of engineering soil classification systems will be considered.

Engineering Grain-Size Scales of the U. S.

5. Engineering grain-size scales were developed from agricultural soil classification systems. The most important departure from the grain-size analysis approach was the system proposed in 1905 by Atterberg[1] in which cohesive soils were classified on the basis of their plastic behavior. In 1913, the International Society of Soil Science[2] adopted Atterberg's classification system as its standard. In 1914, Kopecky[3] introduced a modification to the grain-size standard of the International Society of Soil Science that included a simple and easy to memorize scale based only on the numbers 2 and 6.

6. A comparison of major engineering grain-size scales of the U. S. is shown in Figure 1. Probably the first engineering soil classification system in the U. S. was the grain-size scale developed by the Bureau of Public Roads.[4] For this scale, the following definitions were established:

a. Sand. That part of soil that passes the No. 10 (2.00-mm) sieve* but is retained on the No. 200 (75-μm) sieve and also settles out of a 500-cc soil-water mixture in 8 min.

---

* Sieve sizes in this report are cited throughout by their U. S. standard series designation followed by the SI equivalent in parentheses.

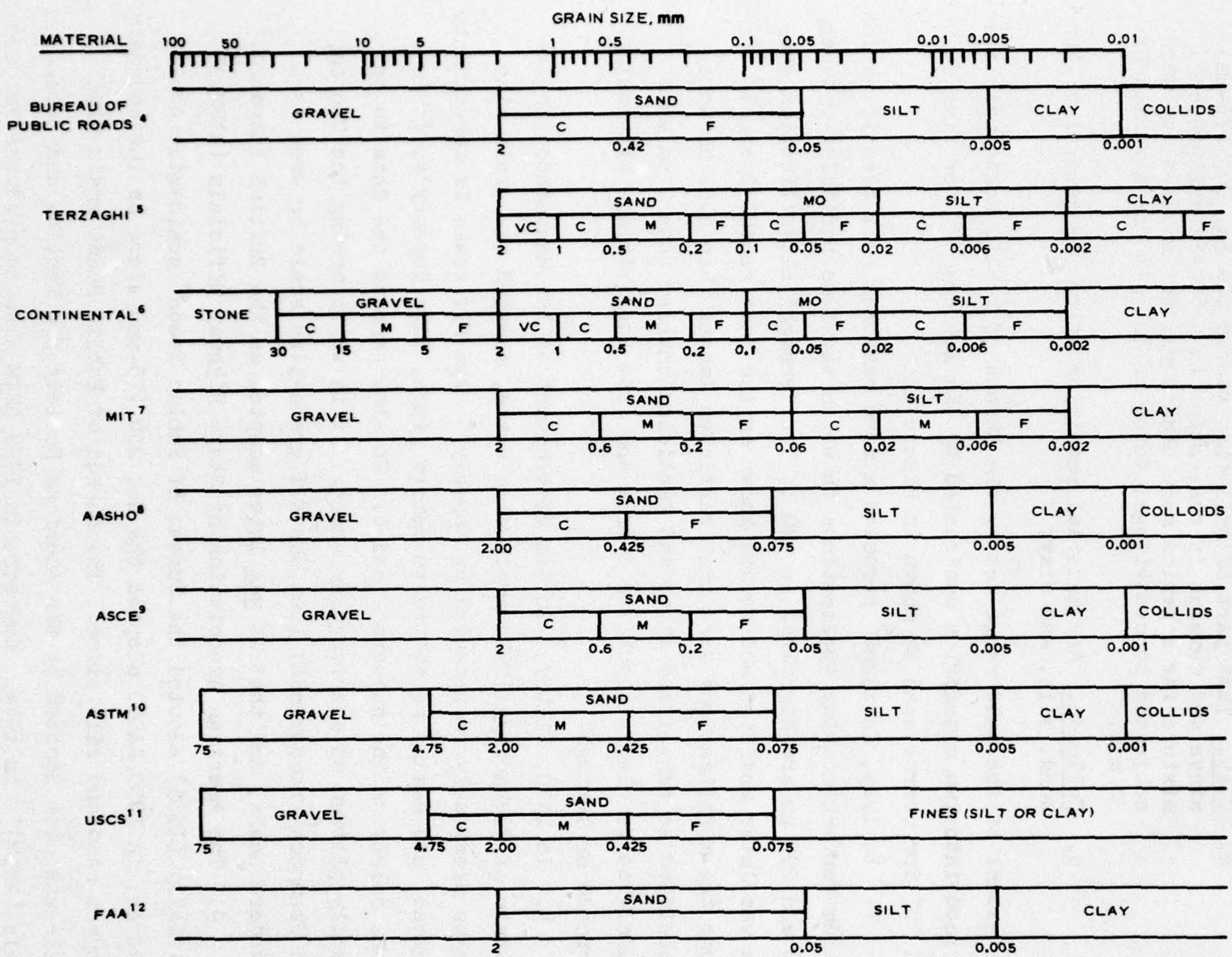


Figure 1. Major engineering grain-size scales of the U. S.

b. Silt. That part of soil that passes the No. 200 (75-μm) sieve and settles out of a 500-cc soil-water mixture in 8 min.

c. Clay. That part of soil that passes the No. 200 (75-μm) sieve and remains in suspension in a 500-cc soil-water mixture for a period more than 8 min but settles out when subjected to centrifugal force of 500 g's for a period of 30 min.

d. Colloids. Any material remaining after the removal of the sand, silt, and clay.

The extent of the sand range set by the Bureau of Public Roads was later divided into two categories designated by the letters "F" for fine sand and "C" for coarse sand as shown in Figure 1.

7. In 1925, Terzaghi[5] proposed a more rational soil classification system for engineering applications in which the fine particles between 100 and 200 μm are described as MO . The Terzaghi classification system was later modified and became known as the Continental System.[6] Among the modifications were that particles larger than 2.00 mm were classified as gravel and stone and particles smaller than 2 μm were classified as clay without the coarse and fine subdivisions originally proposed by Terzaghi.

8. In 1930, Gilboy,[7] in his development of the Massachusetts Institute of Technology (MIT) grain-size scale, adopted the grain-size limits previously recommended by Kopecky.[3] The MIT scale is convenient, logical, and easily committed to memory since, like Kopecky's, it is based solely on the numbers 2 and 6. It also permits the data to be readily plotted on a triangular chart. It is worth noting the Glossop and Skempton[6] recommended that the MIT grain-size scale be used as a standard scale, and that it was later adopted as the British standard.[13]

9. The American Association of State Highway Officials (AASHO)[14] initially (1935) adopted the Bureau of Public Roads[4] grain-size scale. However, in 1950 AASHO adopted the No. 200 (75-μm) sieve as the boundary between sand and silt sizes. The Bureau of Public Roads grain-size scale was also adopted by the American Society for Testing and Materials (ASTM)[15] in 1944. However, in 1958 ASTM also adopted the No. 200

(75-μm) sieve sand-silt boundary and also fixed the upper limit of sand sizes as the No. 4 (4.75-mm) sieve.

10. By 1942, the Office, Chief of Engineers (OCE), U. S. Army, was finding it increasingly difficult to design airfield pavements on a world-wide basis given the soil classification systems in existence at that time. Consequently, OCE commissioned Professor Arthur Casagrande to develop a new classification system which became known as the Airfield Classification (AC) system.[16] In this system, soils are not only classified based on their grain sizes, but also based on their plasticity, uniformity, and behavior as construction material.

11. With the experience gained in using the original AC system, the U. S. Army Engineer Waterways Experiment Station (WES), in cooperation with the Bureau of Reclamation, expanded the classification system in 1953[17] and then modified it in 1960[11] to develop what is now known as the Unified Soil Classification System (USCS). The grain-size scale adopted for the USCS is shown in Figure 1. In the USCS, the terms "silt" and "clay" are used to distinguish materials based on their plasticity characteristics rather than grain sizes. The minus No. 200 (75-μm) sieve material is classified as silt if the liquid limit (LL) and plasticity index (PI) plot below the "A" line on the plasticity chart (shown in Figure 2) and is classified as clay if the LL and PI plot above the "A" line on the chart. In this classification system, all consistency limits are determined on the minus No. 40 (425-μm) sieve fraction of the soil.

12. In 1957, the Highway Division Committee[9] of the American Society of Civil Engineers (ASCE) proposed a grain-size scale for highway material which is similar to the Bureau of Public Roads[4] scale with the exception that sand is subdivided into three categories instead of two. These groups are defined by 2.00-mm to 600-μm particles for coarse sand, 600- to 200-μm particles for medium sand, and 200- to 50-μm particles for fine sand.

13. Another grain-size scale was developed in 1967 by the Federal Aviation Administration (FAA)[12] which is similar to the AASHO scale with the exception that it considers only the material which passes the

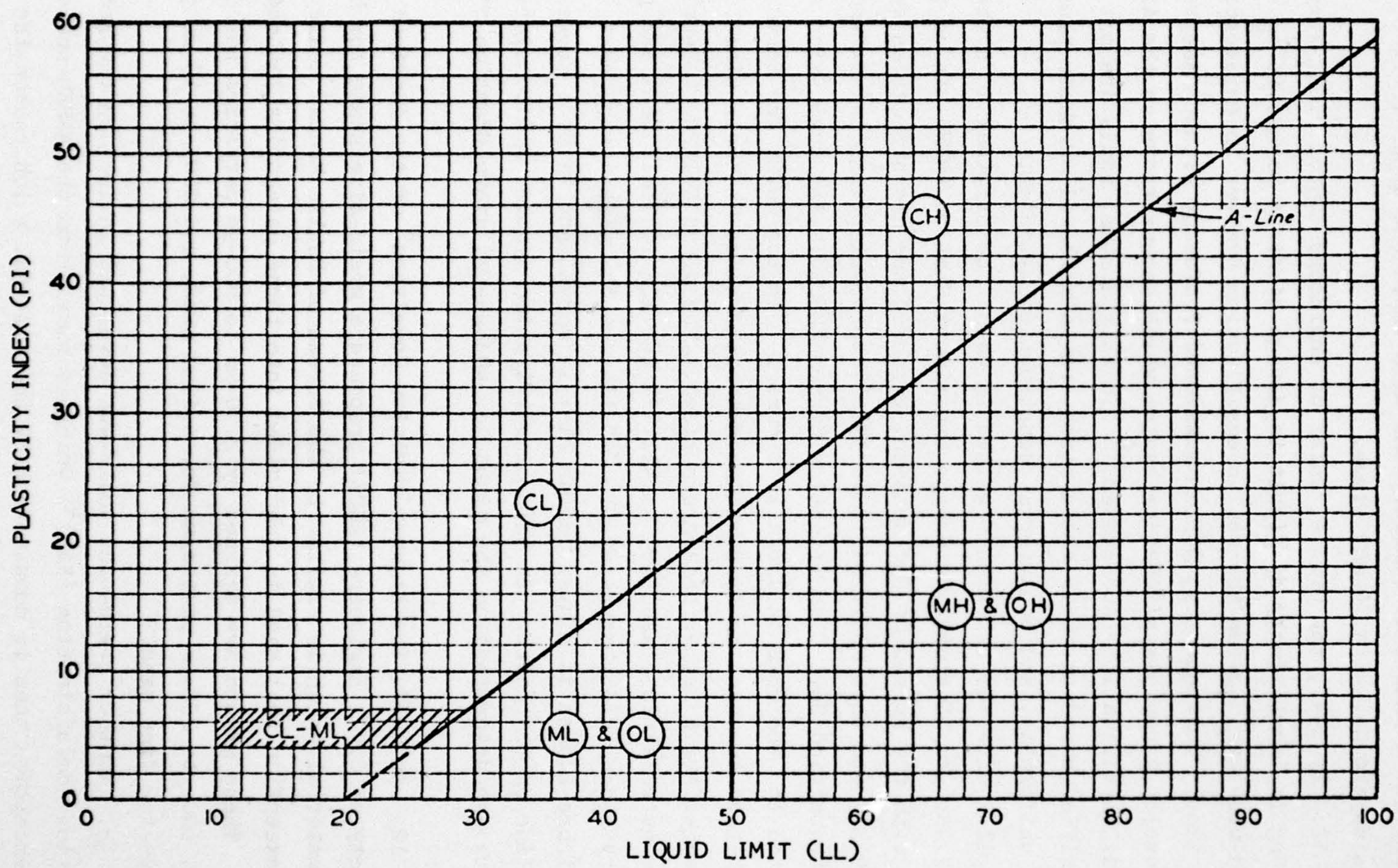


Figure 2. Plasticity chart for the USCS

No. 10 (2.00-mm) sieve; therefore, anything larger than sand is not considered.

Some European Grain-Size Scales

14. Figure 3 summarizes several European grain-size scales used for the engineering classification of soils. The British grain-size scale, as outlined in CP 2001 dated 1957,[18] is basically similar to the MIT[7] grain-size scale with the exception that gravel is also subdivided into three categories, coarse, medium, and fine, as shown in Figure 3. In 1959, the Swiss Association of Standards[19] published a soil classification system based on the USCS with a grain-size scale similar to that of MIT. A similar classification system was published by Schon[20] for the French Central Laboratory for Bridges and Roads. The French grain-size scale is similar to the MIT scale with the exception that the limit between sand and silt is 80 μm rather than 60 μm. The German grain-size scale[21] is similar to the British with the exception that the silt portion of the soil is not subdivided. The Hungarian Standard[22] somewhat parallels the International Society of Soil Science scale.[2]

Summary of Grain-Size Scales

15. Engineering grain-size scales attempt to separate soils into groups that have similar potential engineering properties and behavior. Basically, all grain-size limits are arbitrary because no clear-cut division can be made among soils of continuous grain-size distribution. Although the grain-size scales shown in Figures 1 and 3 are different in detail, they are similar in concept. The range of grain-size separation, as shown in Figure 4, between "coarse" material which is determined by sieve analysis and "fine" material which is determined by hydrometer analysis, whether based on the No. 200 (75-μm) sieve or the No. 270 (53-μm) sieve, is very narrow. Either limit can be used without introducing significant error since for cohesive soil the engineering properties are considerably more affected by the plasticity characteristics

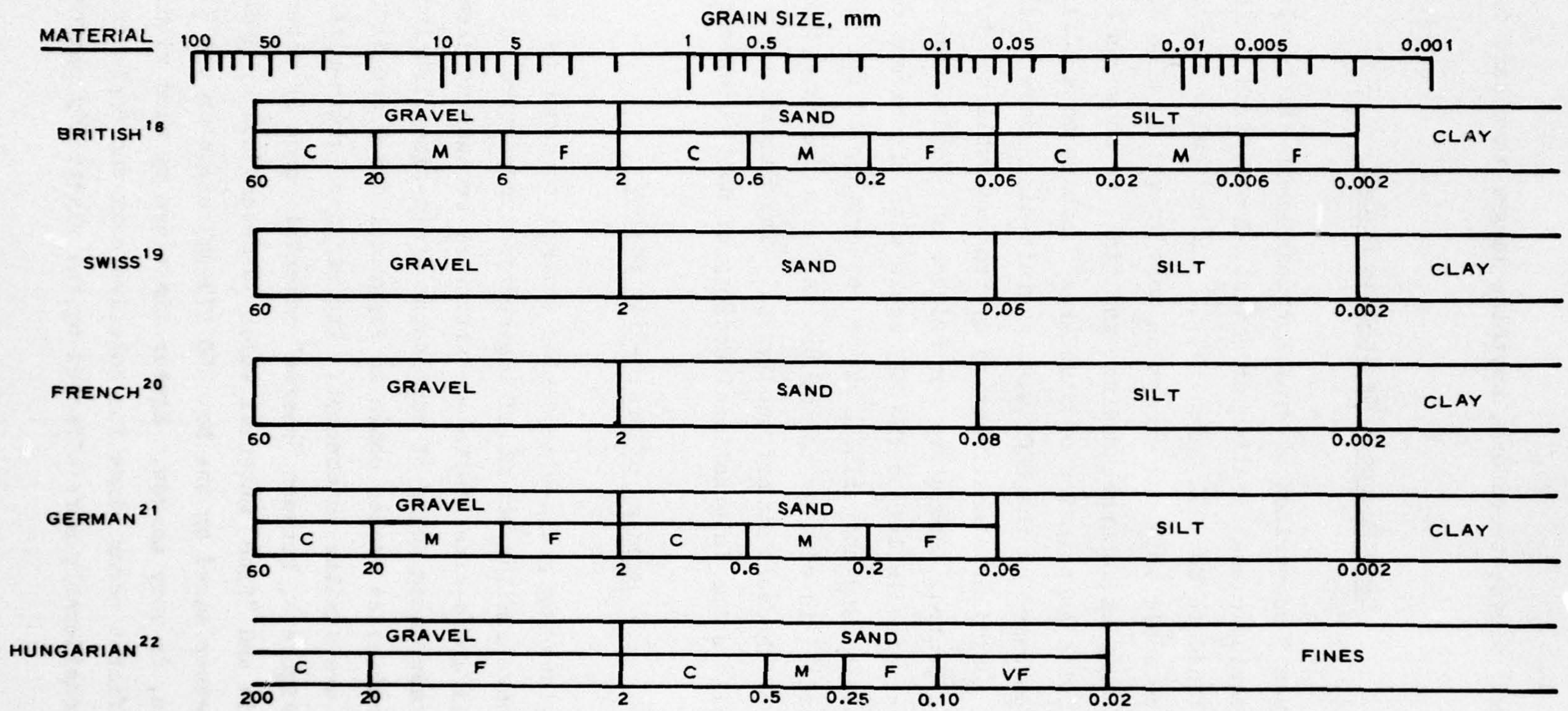


Figure 3. European grain-size scales

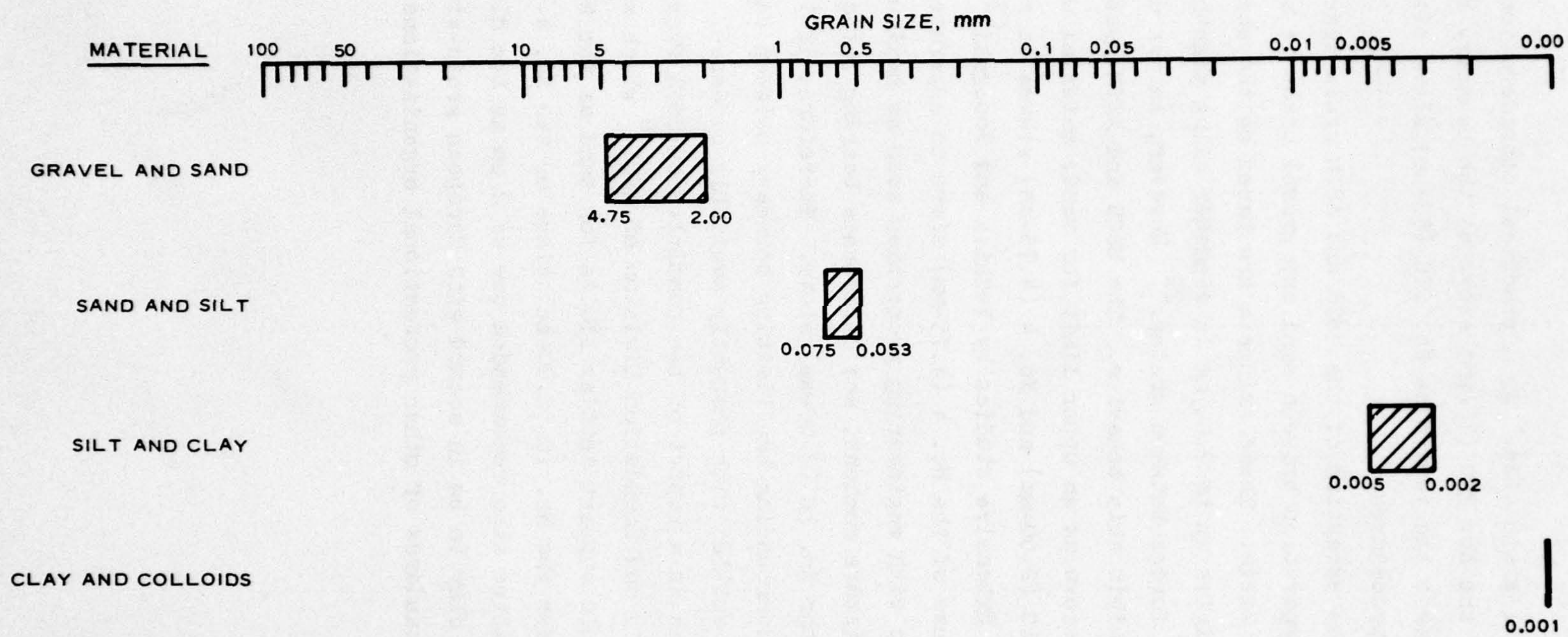


Figure 4. Spread in limit of separation between major soil grain sizes

than by the actual grain size. As a practical consideration, it is easier to employ the No. 200 (75-μm) sieve as the boundary between sand and silt sizes since the very fine No. 270 (53-μm) sieve often requires special sieving procedures.

16. With the exception of the USCS and ASTM grain-size scales (see Figure 1), the separation between sand and gravel sizes is made at the No. 10 (2.00-mm) sieve. These criteria are based on the observation that coarse particles up to 2.00 mm in diameter cling together when wet due to capillary forces between grains.[22] However, larger diameter particles do not exhibit this behavior. The USCS and ASTM system use the No. 4 (4.75-mm) sieve as an upper limit for sand; material with sizes between the No. 10 (2.00-mm) and No. 4 (4.75-mm) sieves is referred to as coarse sand. Extensive studies by Veshita and Nonogaki[23] in Japan have shown that use of the No. 4 (4.75-mm) sieve to separate sand from gravel correlates with engineering properties such as maximum dry density, optimum moisture content, and California bearing ratio (CBR) better than use of the No. 10 (2.00-mm) sieve. Therefore, it is clear that the controversy surrounding the limiting boundary between sand and gravel cannot be settled with presently available evidence. Such sentiment was expressed in a report of the Committee on Soil Properties of the Soil Mechanics and Foundation Division of ASCE[24] which stated that the committee could support setting limits for sand as the No. 200 (75-μm) sieve to either the No. 10 (2.00-mm) sieve or the No. 4 (4.75-mm) sieve. The committee also recommended use of 2 μm as the dividing line between silt and clay to be in accord with European grain-size scales as well as the standards of other professional organizations within the U. S.

PART III: ENGINEERING SOIL CLASSIFICATION SYSTEMS

17. Many classification systems have been developed to serve a particular need or to deal with the special characteristics of a given soil. By necessity, each system has been designed with specific objectives in mind. Only a few classification systems have been comprehensive enough to receive reasonably wide acceptance. And only rarely has any particular classification system provided the designer with all the soil information needed to complete a given job. An examination of some of the more commonly used engineering soil classification systems is presented in this part.

Commonly Used U. S. Systems

AASHO system

18. In 1929, the Bureau of Public Roads introduced a soil classification system for road design and construction. Since that time, the system has gone through many modifications and revisions as more information has become available regarding highway subgrades and embankments. The most significant revision was made in 1945 by the Highway Research Board,[25] and the system has since become known as the Highway Research Board system, the Modified Bureau of Public Roads system, or the AASHO system.

19. Soils in this system, as summarized in Table 1 and Figure 5, are divided into two major groups:

a. Granular materials. Contain 35 percent or less material passing the No. 200 (75-μm) sieve.

b. Silt-clay materials (fines). Contain more than 35 percent material passing the No. 200 (75-μm) sieve.

The grain-size scale used in this system is presented in Figure 1. In this system, the classifications A-1 through A-7, as shown in Table 1, indicate decreasing quality of material for highway use with increasing number. The classification is supplemented by a useful parameter called the Group Index which is used for correlation as indicated in Table 1.

Table 1

AASHO Soil Classification System

(Classification of Highway Subgrade Materials)

General Classification	Granular materials (35% or less passing No. 200)			Silt-clay materials (more than 35% passing No. 200)			
Group Classification	A-1	A-3	A-2	A-4	A-5	A-6	A-7
Sieve analysis, percent passing							
No. 10							
No. 40	50 max	51 min					
No. 200	26 max	10 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40:							
Liquid limit				40 max	41 min	40 max	41 min
Plasticity index	6 max	NP		10 max	10 max	11 min	11 min
Group index				8 max	12 max	16 max	20 max
General rating as subgrade		Excellent to good			Fair to poor		

(Subgroups)

General Classification	Granular material (35% or less passing No. 200)							Silt-clay materials (more than 35% passing No. 200)			
	A-1		A-3	A-2							
Group Classification	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7 A-7-5, A-7-6
Sieve analysis, percent passing											
No. 10	50 max										
No. 40	30 max	50 max	51 min								
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40:											
Liquid limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Group index	0		0	0		4 max		8 max	12 max	16 max	20 max
Usual types of significant constituent materials	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade				Excellent to good					Fair to poor		

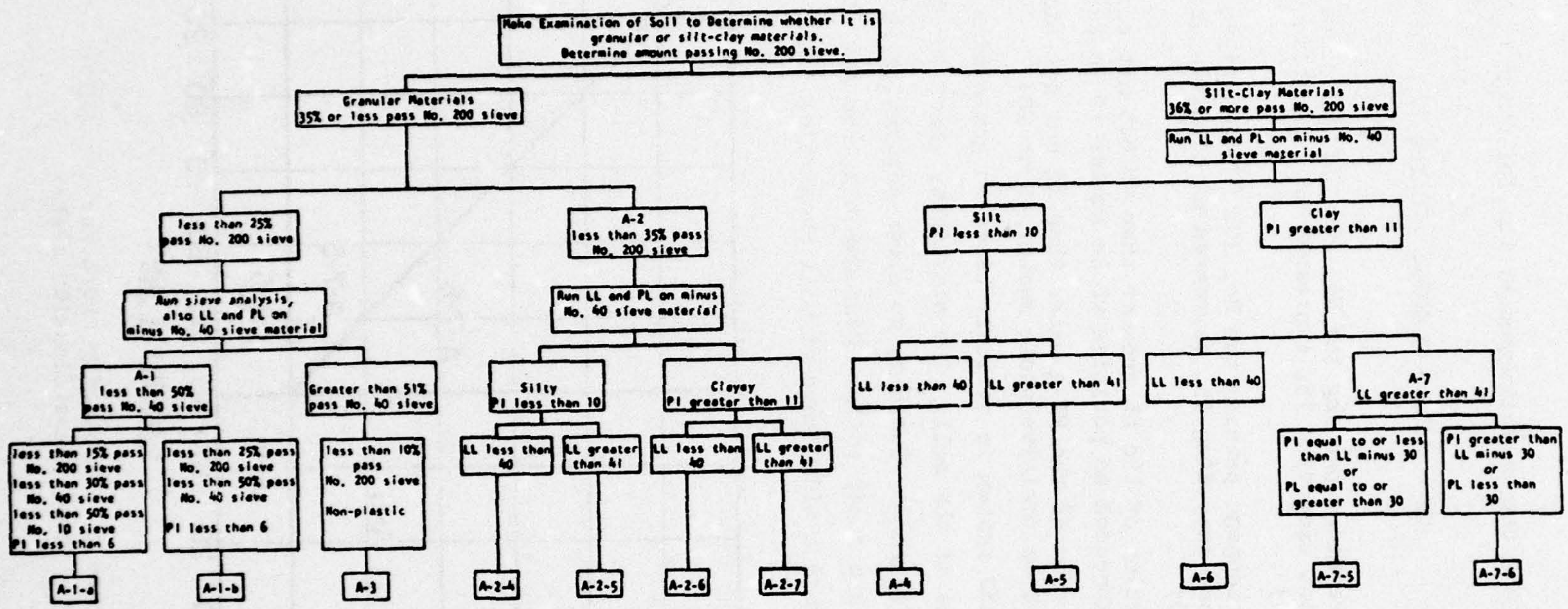


Figure 5. AASHO soil classification chart

The Group Index (GI) can be expressed by the following:

$$GI = 0.2a + 0.005ac + 0.1bd \qquad (1)$$

where

a = that percentage passing the No. 200 (75-μm) sieve greater than 35 but not exceeding 75, expressed as a positive whole number (0 to 40)

b = that percentage passing the No. 200 (75-μm) sieve greater than 15 but not exceeding 55, expressed as positive whole number (0 to 40)

c = that portion of the LL greater than 40 but not exceeding 60 percent, expressed as positive whole number (0 to 20)

d = that portion of the PI greater than 10 but not exceeding 30, expressed as positive whole number (0 to 20)

20. The AASHO system is strictly based on grain size and the plastic properties of the soil. The plasticity chart for the AASHO system is shown in Figure 6. There is no clear separation in this system between gravelly and sandy soils. Consequently, the A-2 classification (see Table 1) covers a wide range of soil properties. The separation

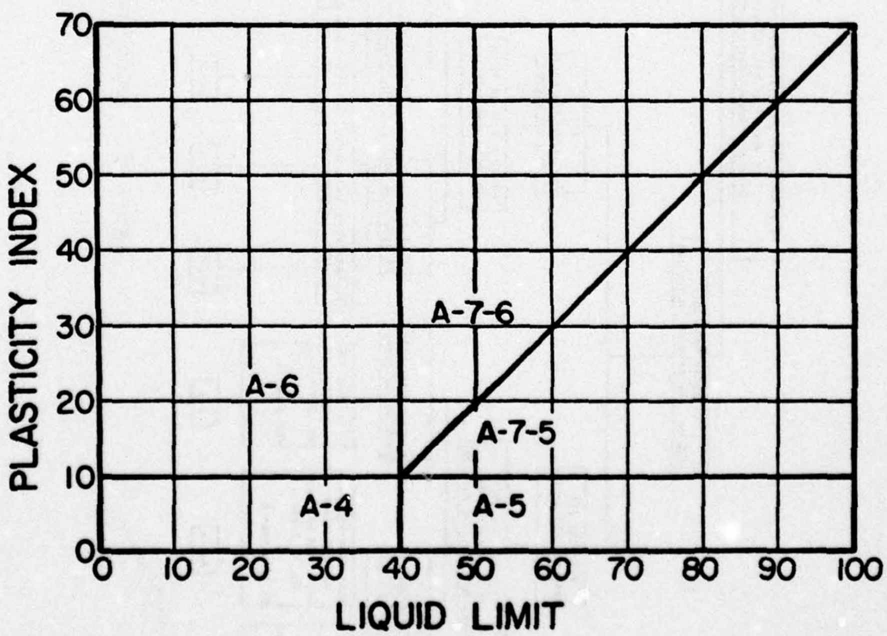


Figure 6. Plasticity chart for the AASHO soil classification system

of the A-1, A-2, and A-3 classifications is not well defined since it is likely that a granular soil with less than 25 percent passing the No. 200 (75-μm) sieve may not fulfill the other requirement to be classified either A-1 or A-2. The AASHO system, however, has been used successfully in rating soil as subgrade material for many years.

FAA system

21. Another major soil classification system based on grain size and plasticity is the one developed by the FAA.[12] In this system (see Table 2 and Figure 7), soils are divided into 13 groups designated E-1 to E-13, with increasing numbers indicating poorer quality material. The soil grain-size limits of the FAA are similar to those of the AASHO system (Figure 1) with the exception that the FAA system only considers material passing the No. 10 (2.00-mm) sieve; i.e., gravel is not considered. The No. 200 (75-μm) sieve is used to separate the coarse from the fine fraction of the soil. The silt and clay portions of the fine fraction used in the classification are based on the LL and PI as shown in Figure 8. This classification system is unsuitable for general usage since it does not consider the gravel sizes.

USCS

22. The USCS,[11] as shown in Figure 9, classifies soils into three major groups:

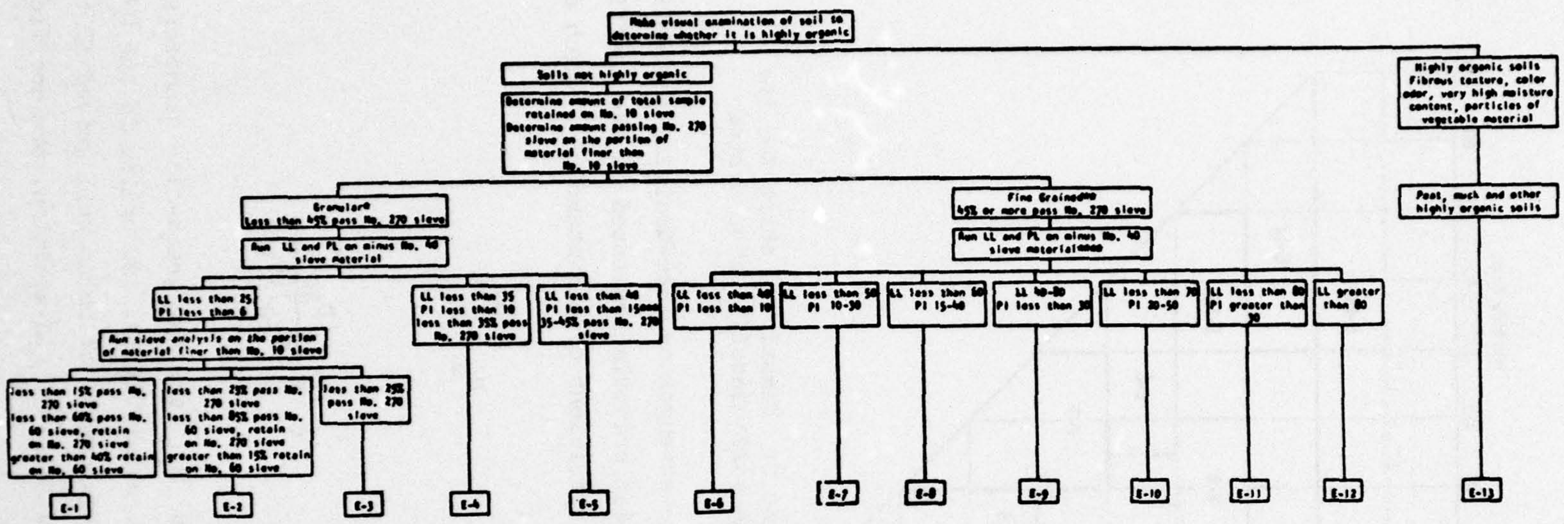
- a. Highly organic soils.
- b. Coarse-grained soils. Contain 50 percent or more material by weight retained on the No. 200 (75-μm) sieve.
- c. Fine-grained soils. Contain more than 50 percent material passing the No. 200 (75-μm) sieve.

The grain-size scale used in this system is presented in Figure 1. Letter symbols are employed to designate the classification. For coarse-grained soils, the letter G (gravel) is used if more than 50 percent of the coarse particles (plus No. 200 (75-μm) sizes) is retained on the No. 4 (4.75-mm) sieve, and the letter S (sand) is used if less than 50 percent is retained. If the soil contains less than 5 percent fines, the G or S designation is supplemented by a second letter to describe the nature of the grain-size distribution: W for well graded if the

Table 2

FAA Soil Classification System

	Mechanical Analysis					
		Material Finer Than No. 10 Sieve				
Soil Group	Retained on No. 10 Sieve (%)	Coarse Sand, Pass No. 10 Ret. No. 40 (%)	Fine Sand, Pass No. 40 Ret. No. 200 (%)	Combined Silt and Clay, Pass No. 200 (%)	Liquid Limit	Plasticity Index
E-1	0-45	40+	60-	15-	25-	6-
E-2	0-45	15+	85-	25-	25-	6-
E-3	0-45	--	--	25-	25-	6-
E-4	0-45	--	--	35-	35-	10-
E-5	0-55	--	--	45-	40-	15-
E-6	0-55	--	--	45+	40-	10-
E-7	0-55	--	--	45+	50-	10-30
E-8	0-55	--	--	45+	60-	15-40
E-9	0-55	--	--	45+	40+	30-
E-10	0-55	--	--	45+	70-	20-50
E-11	0-55	--	--	45+	80-	30+
E-12	0-55	--	--	45+	80+	--
E-13	Muck and peat-field examination					



* When the percentage of the total sample retained on the No. 10 sieve exceeds 45%, upgrading from 1 to 2 classes may be permitted, provided the coarse fraction is reasonable sound and fairly well graded.

** When the percentage of the total sample retained on the No. 10 sieve exceeds 55%, upgrading from 1 to 2 classes may be permitted, provided the coarse fraction is reasonable sound and fairly well graded.

*** A plasticity index greater than 15 would cause the soil to be classified with fine grained soils even though it may contain less than 45% pass No. 270 sieve.

**** If test results on fine grained soils place the soil in more than one group, the appropriate soil group must be determined from the plasticity chart.

Figure 7. FAA soil classification system chart

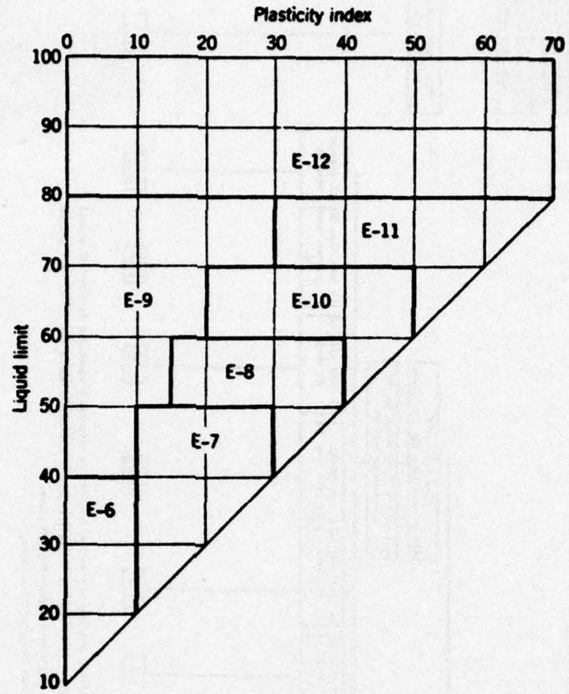


Figure 8. Plasticity chart for the FAA soil classification system

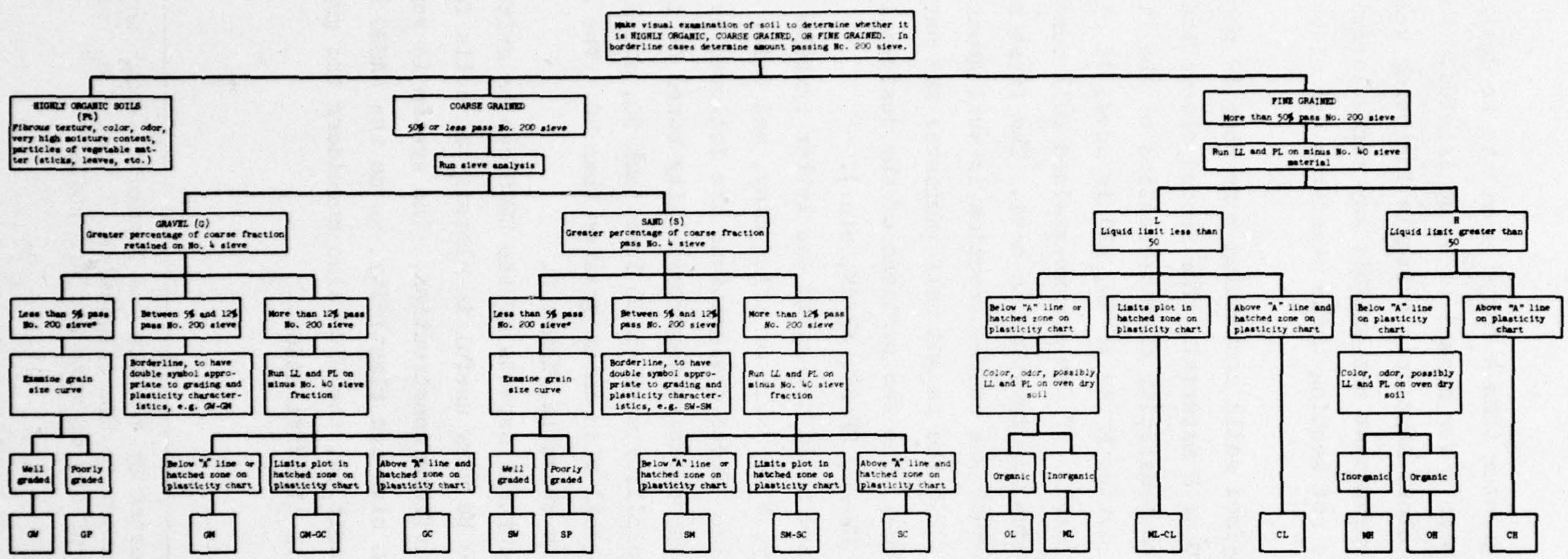
fines do not affect the strength or free-draining properties, and P for poorly graded. Gradation criteria are based on the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) which are defined by

$$C_u = \frac{D_{60}}{D_{10}} \tag{2}$$

and

$$C_c = \frac{(D_{30})^2}{(D_{60})(D_{10})} \tag{3}$$

where D_{60} , D_{30} , and D_{10} are the grain-size diameters at 60, 30, and 10 percent passing, respectively. According to the USCS, a gravel or sand fulfills one requirement of being well graded if the coefficient of curvature is between 1 and 3. In addition, the coefficient of



Note: Sieve sizes are U. S. Standard.

* If fines interfere with free draining properties use double symbol such as GW-GM, etc.

Figure 9. USCS chart

uniformity must be greater than 4 for a gravel to be designated as well graded and greater than 6 for a sand to be so labeled. Furthermore, even if both of the above-mentioned criteria for being well graded are met, the gradation curve must not exhibit any irregularities of shape. Coarse-grained soils not meeting these standards are classed as poorly graded.*

23. Coarse-grained soils containing more than 12 percent fines are also classified as G or S material. The second classification letter is selected based on the plasticity characteristics of the fines. If the fines are silt, the letter M (as in GM, SM) is used; if clay, the letter C (as in GC, SC) is used. If the coarse-grained soil contains 5 to 12 percent fines, a dual designation is used. The first half of the symbol indicates whether the coarse fraction is well graded or poorly graded (GW, GP, SW, SP); the second half indicates the nature of the fines (GM, GC, SM, SC). The two portions of the designation are joined by a hyphen (GW-GC, GW-GM, SP-SC, SP-SM, etc.).

24. Fine-grained soils are given the letter symbols C for clay or soil containing clay, M for silt or silty clay, and O for organic clay or organic silt soils. These designations are followed by a second letter to indicate the relative compressibility based on the LL; L indicates low compressibility with an LL less than 50, and H indicates a highly compressible soil with an LL greater than 50. The plasticity chart for the USCS is shown in Figure 2.

25. Although certain aspects of the USCS can be criticized, the system has proven to be very useful in classifying soils for embankment, dam, highway, and airfield construction. The system is very simple and relies on both grain size and plasticity, as do the AASHO and FAA systems; however, in addition, the USCS also considers the grain-size distribution in the soil classification.

---

* It has been suggested by Veshita and Nonogaki[23] that any material which does not conform to the expression $1 < C_c < C_u$ is gap graded; i.e. is a mixture of two or more uniform soils.

Comparison of the USCS and
the AASHO and FAA systems

26. The three commonly used U. S. systems recognize two main soil groups: the coarse-grained or granular group comprising gravel and sand, and the fine-grained or cohesive group comprising silt and clay. Soils in the coarse-grained group are classified primarily on the basis of grain size, and soils in the fine-grained group are classified on the basis of plasticity. It should be noted, however, that the grain-size limits within the coarse-grained group used by each system, as indicated in Figure 1, are different and that the criteria used to categorize the fine-grained group of each system are also different. All three systems require no more than a grain-size analysis and tests for Atterberg limits for the soil classification.

27. The major differences in the AASHO and FAA systems and the USCS are presented in Figure 5, 7, and 9. These figures show that the USCS has the greatest number of soil groups, making it appear to be the most complicated, while the AASHO system has the least number of soil groups. However, if the organic groups are ignored, as is the case in the AASHO system, then the three systems have the same number of soil groups. On the other hand, the USCS is the most logical and concise system since it follows a step-by-step scheme without ambiguity. It has been shown through comprehensive tests[26,27] that the "A" line in the USCS plasticity chart (Figure 2) serves as the best criteria for separating clay from silt. The PI of 10 used to separate clay from silt in the AASHO system seems to be arbitrary and does not realistically reflect the properties of fine-grained soils. The separation between silt and clay in the FAA system is made based on grain size and not plastic properties. As can be seen in Figure 1, the three systems have different limits in separating gravel size from sand size and also sand size from silt size. The range of the sand sizes is 4.675 mm in the USCS, 1.925 mm in the AASHO system, and 1.95 mm in the FAA system.

28. The USCS employs simple and logical symbols which, with the exception of the letter M used for silt, reflect the name of each soil group. However, both the AASHO system and the FAA system employ a

single letter associated with a number that serves as a rating of the desirability of that soil group for pavement construction. (There is no particular significance in the use of the letter "A" in the AASHO system and the letter "E" in the FAA system. It should also be pointed out that the field procedure of the USCS[11,28] can be easily used by an individual with little or no laboratory training. It is also possible to classify soil in the field according to the AASHO system even though the system does not have a standard procedure. It is, however, difficult if not impossible to classify soil according to the FAA system in the field.

29. It is evident that the criteria adopted for the AASHO and FAA systems and the USCS are different. Thus, any comparison of soil groups across these systems is a difficult task. However, because of the popularity and the wide acceptance and use of these systems, it is frequently very helpful to draw direct comparisons between soil groups of these three systems. Probably the best and the most concise comparison is the one made by Liu[29] and summarized in Table 3.

30. Because there are so many different soil properties of interest and so many possible combinations of soils, it would be extremely difficult if not impossible to develop a universally accepted system. Each classification system has been designed to serve a particular engineering usage, omitting consideration of engineering properties that are very important in other engineering applications. Such omissions are among the common limitations of all soil classification systems. It is important for those who depend on soil classifications to be familiar with the purpose and the limitations of the systems they are using, especially when they are unfamiliar with the soil they are classifying. This point is perhaps best stated by Casagrande:[16] "...Those who really understand soil can, and often do, apply soil mechanics without any formally accepted soil classification."

Other Systems

31. Two other classification systems, both essentially based on the USCS, have recently been developed. The first was developed in

Table 3

Comparable Soil Groups for USCS (after Liu[29])

Soil Group in USCS	Comparable Soil Groups in FAA System: Most Probable	Possible	Possible but Improbable	Comparable Soil Groups in AASHO System: Most Probable	Possible	Possible but Improbable
GW	E-1	--	--	A-1-a	--	A-2-4, A-2-5, A-2-6, A-2-7
GP	E-1	--	--	A-1-a	A-1-b	A-3, A-2-4, A-2-5, A-2-6, A-2-7
GM	E-2, E-4, E-5	--	E-1, E-6, E-7, E-8, E-9, E-10, E-11, E-12	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6	A-4, A-5, A-6, A-7-5, A-7-6, A-1-a
GC	E-5	E-4	E-6, E-7, E-8, E-10, E-11, E-12	A-2-6, A-2-7	A-2-4, A-6	A-4, A-7-6, A-7-5
SW	E-1	--	--	A-1-b	A-1-a	A-3, A-2-4, A-2-5, A-2-6, A-2-7
SP	E-1, E-3	E-2	--	A-3, A-1-b	A-1-a	A-2-4, A-2-5, A-2-6, A-2-7
SM	E-2, E-3, E-4, E-5	--	E-1, E-6, E-7, E-8, E-9, E-10, E-11, E-12	A-1-b, A-2-4, A-2-5, A-2-7	A-2-6, A-4, A-5	A-6, A-7-5, A-7-6, A-1-a

(Continued)

Table 3 (Concluded)

Soil Group in USCS	Comparable Soil Groups in FAA System			Comparable Soil Groups in AASHO System		
	Most Probable	Possible	Possible but Improbable	Most Probable	Possible	Possible but Improbable
SC	E-4, E-5	--	E-6, E-7, E-8, E-10, E-11, E-12	A-2-6, A-2-7	A-2-4, A-6, A-4, A-7-6	A-7-5
ML	E-6, E-7	E-9	E-1, E-2, E-3, E-5	A-4, A-5	A-6, A-7-5	--
CL	E-7	E-6, E-8	E-4, E-5	A-6, A-7-6	A-4	--
OL	E-6, E-7	E-9	E-1, E-2, E-3, E-5	A-4, A-5	A-6, A-7-5, A-7-6	--
MH	E-8, E-9, E-10, E-11, E-12	--	--	A-7-5, A-5	--	A-7-6
CH	E-8, E-10, E-11, E-12	--	--	A-7-6	A-7-5	--
OH	E-8, E-9, E-10, E-11, E-12	--	--	A-7-5, A-5	--	A-7-6
Pt	E-13	--	--	--	--	--

England by Dumbleton[30]; the second was proposed by Veshita and Nonogaki[31] before the Japanese Society of Soil Mechanics and Foundation Engineering.

Dumbleton's system

32. In 1968, Dumbleton[30] proposed a soil classification system which leans heavily on the existing practice of the USCS[11] and the British system,[18] while at the same time attempting to describe soils more systematically. The suggested classification, as shown in Figure 10, assigns boundaries between clean gravels or sands, gravels or sands with some fines, gravels or sands with fines, gravelly or sandy fine soils, and fine soils of 5, 20, 50, and 70 percent fines, respectively. Soils with less than 20 percent fines are further differentiated according to their coefficient of uniformity (C_u) and coefficient of curvature (C_c). The criteria for well graded soil are to have C_u greater than 5 and C_c between 1 and 3. The Atterberg fractions (i.e., that material passing the No. 40 (425-μm) sieve) are classified according to the range into which their LL falls. Dumbleton considers soil with an LL less than 20 to be nonplastic. However, the plastic Atterberg fractions are divided into low, intermediate, high, very high, and extra high LL's which are separated by boundaries of 35, 50, 70, and 90, respectively. Dumbleton retains 2.4 mm as the boundary between gravel and sand sizes as originally adopted in the British system.[18]

Veshita and Nonogaki's system

33. In 1971, Veshita and Nonogaki[31] reported a study of the classification systems for coarse-grained soils with respect to their maximum density, optimum moisture content, soaked CBR, and coefficient of permeability of compacted soil. Their classification system (Figure 11) assigns boundaries between clean gravels or sands, gravels or sands with some fines, gravels or sands with fines, and fine soils of 5, 15, and 50 percent fines, respectively. Gravels and sands are also classified by their C_u and C_c as follows: $C_u < 10$ is a poorly graded soil with uniform grading; $C_u < 1$ or $C_c > \sqrt{C_u}$ is a poorly graded soil with gap grading; and $C_u > 10$ and $1 < C_c < \sqrt{C_u}$ is well graded soil. The fine-grained soils are classified as having desirable fines if the LL ≤ 28 and the PI ≤ 6, undesirable fines if the LL > 28 and the PI < 0.73

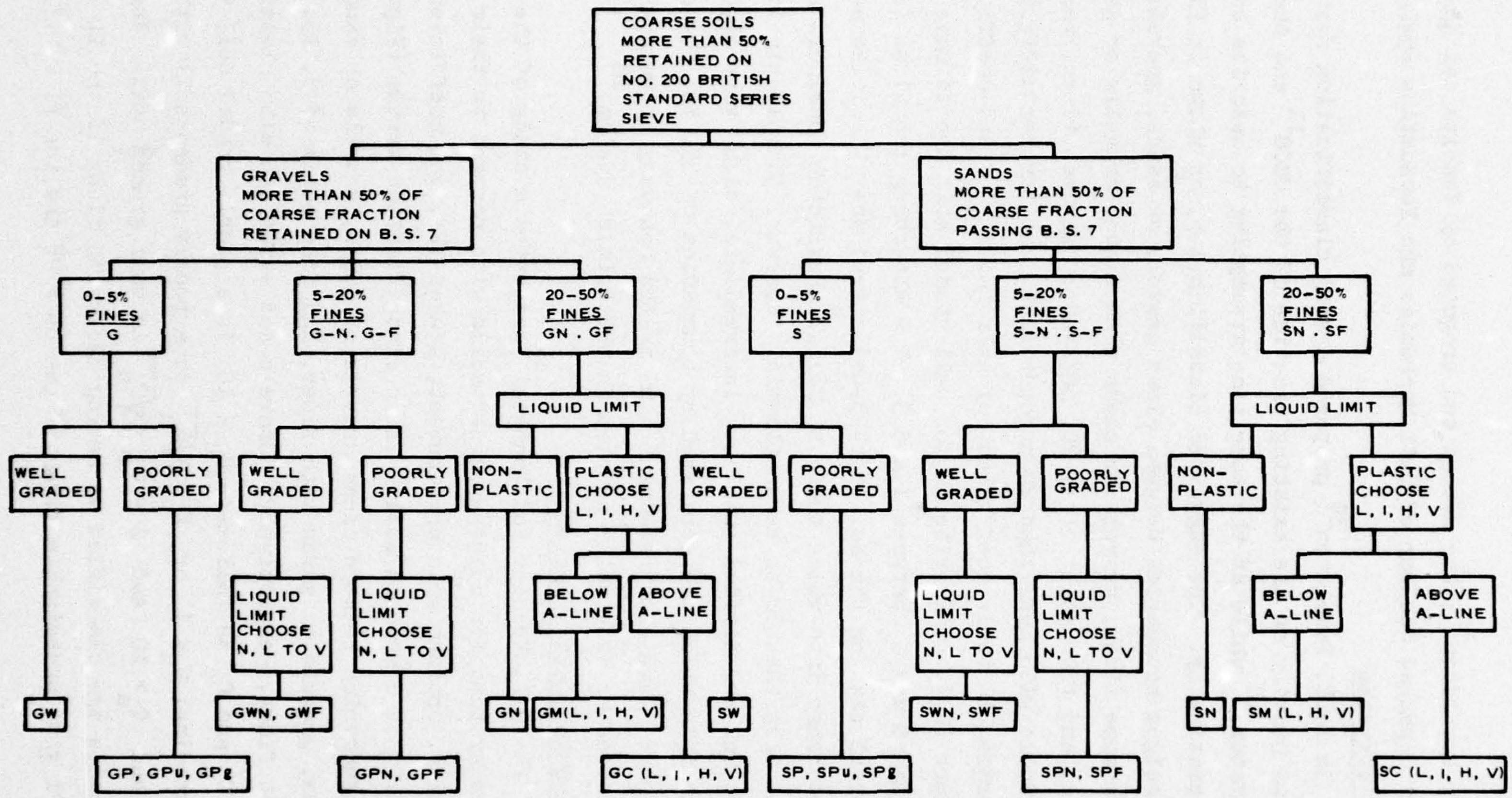


Figure 10. Classification system for coarse-grained soils suggested by Dumbleton[30]

(LL - 20), and clayey fines if the PI $\geq$ 0.73 (LL - 20) and the PI > 6. Veshita and Nonogaki also propose use of the No. 10 (2.00-mm) sieve as the boundary between gravel and sand sizes.

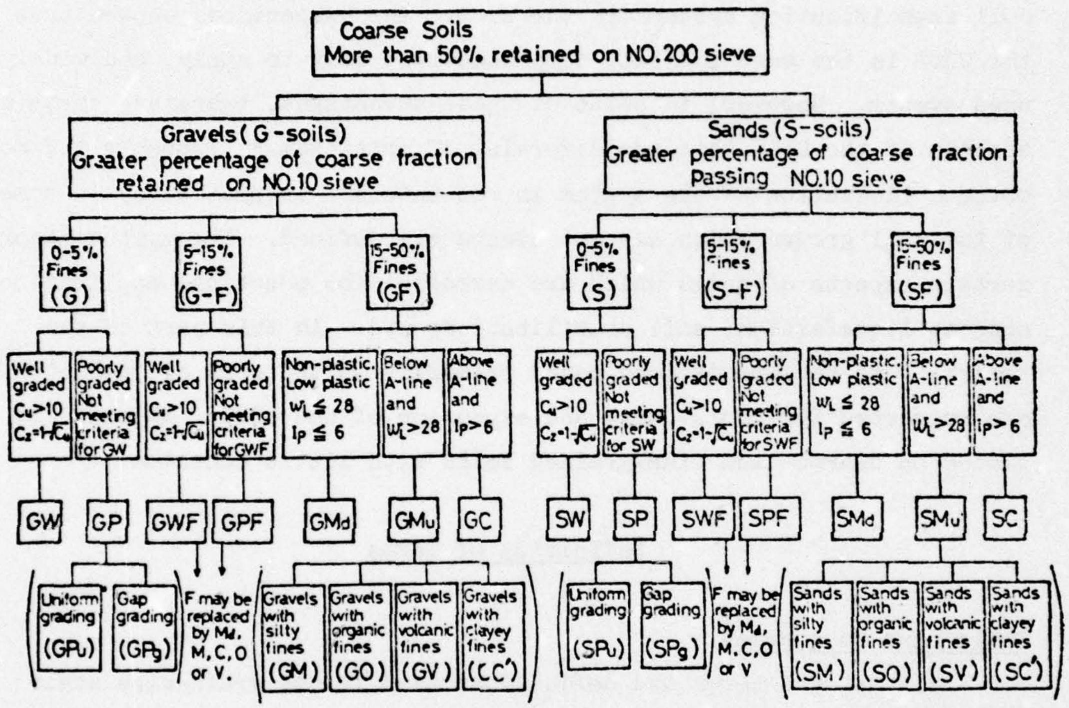


Figure 11. Classification system for coarse-grained soils suggested by Veshita and Nonogaki[31]

PART IV: SUGGESTED EXPANSION OF THE USCS

34. In Part III of this report, comparisons were drawn between the AASHO and FAA systems and the USCS which are by far the most widely used soil classification systems in the U. S. The comparisons showed that the USCS is the most logical, comprehensive, easy to apply, and widely used system. However, in spite of these advantages, there are certain aspects of the USCS that are deserving of criticism.* Probably the most obvious limitation of the system is the internal inconsistency in some of the soil groups which are not adequately defined. The system ignores certain aspects of soils which are essential for practical application such as liquefaction, soil stabilization, etc. In this part of the report, some recommendations based primarily on the work of Dumbleton[30] are suggested for improvement and expansion of the USCS. Emphasis is placed on coarse- and fine-grained soils with little cohesion.

Definition of Terms

Grain size boundaries

35. All the terms and definitions used in the grain-size scale of the USCS will be retained except as stated. The fine fraction of the soil should be divided into two sizes: the silt size, which is composed of soil particles larger than 2 μm, and the clay size, which is composed of particles smaller than that size. However, all plastic fines should be called clays; those whose Atterberg fraction, or material passing the No. 40 (425-μm) sieve, falls below the "A" line (see Figure 12) will be designated M clays, and those whose Atterberg fraction falls above the "A" line will be designated C clays. In terms of U. S. standard series sieve sizes, the limiting boundaries between the size ranges are set as follows:

---

* Examples of which are evident from the recommendations of Dumbleton[30] and Veshita and Nonogaki[31] for improving the USCS system which were presented in Part III.

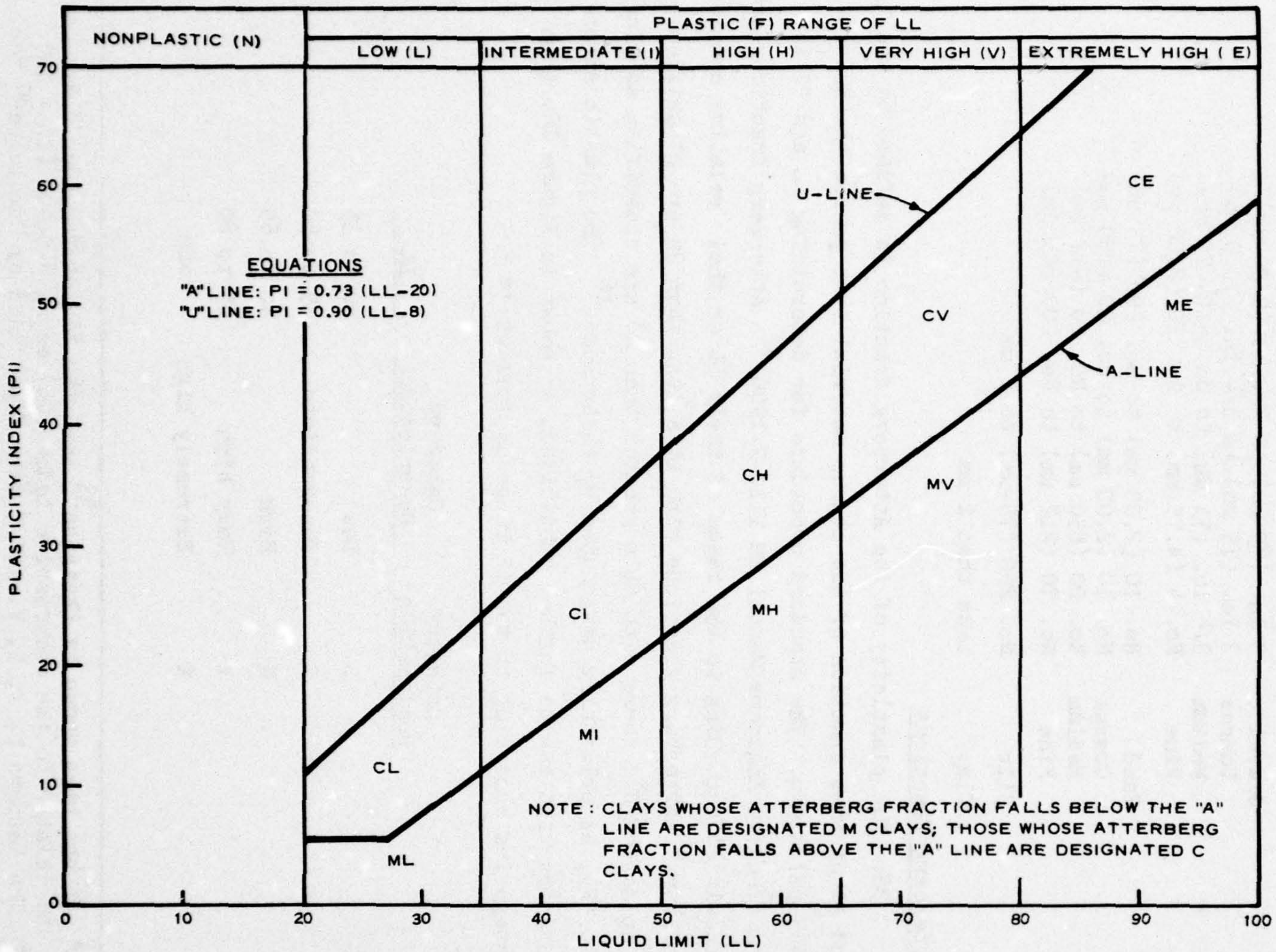


Figure 12. Plasticity chart for classification of the Atterberg fraction

Material	Size Range
Cobbles	Greater than 3 in. (75 mm)
Gravel	3 in. (75 mm) to No. 10 (2.00 mm)
Coarse	3 in. (75 mm) to 3/4 in. (19.0 mm)
Medium	3/4 in. (75 mm) to No. 4 (4.75 mm)
Fine	No. 4 (4.75 mm) to No. 10 (2.00 mm)
Sand	No. 10 (2.00 mm) to No. 200 (75 μm)
Coarse	No. 10 (2.00 mm) to No. 20 (850 μm)
Medium	No. 20 (850 μm) to No. 70 (212 μm)
Fine	No. 70 (212 μm) to No. 200 (75 μm)
Silt	No. 200 (75-μm) to 2 μm
Clay	Less than 2 μm

Atterberg fractions

36. The plasticity of the Atterberg fraction is defined by the LL and PI of that fraction of the coarse material that passes the No. 40 (425-μm) sieve. The standard procedure for determining LL and PI is described in Engineer Manual EM 1110-2-1906.[32] Atterberg fractions are classified according to the range of their LL or their relative compressibility.* Atterberg fractions with LL's less than 20 are classified as nonplastic (N); those with LL's greater than 20 are classified as plastic (F), as originally designated by Casagrande.[16] The plastic Atterberg fraction can be further subdivided, as shown in Figure 12, into categories according to the LL range as follows:**

Category Designation	Category Description	LL
L	Low	20 to 35
I	Intermediate	35 to 50
H	High	50 to 65
V	Very high	65 to 80
E	Extremely high	>80

* It has been shown by Skempton[33] that the LL for remolded clays can be related to the compressive index (C_c) as $C_c = 0.009\ (LL - 10)$.

** The letters L, I, H, V, and E were first used by Dumbleton[30] for classifying the plastic Atterberg fraction and hence are consistent with the revised British system.

37. The letters N, F, L, I, H, V, and E used to classify coarse-grained soils with some fines can be used in the same manner as the letters L and H are presently used in the USCS.

Descriptive terms

38. The guideline which is used to relate the presence of fines in the coarse fraction within the USCS is based on the criteria for selecting the compaction method (i.e., impact or vibratory). When a soil contains less than 5 percent fines, it is ordinarily considered to be a free-draining material and the maximum density can be obtained using the vibratory compaction method. If the percentage fines is increased, the material loses its drainage quality and the effectiveness of the vibratory method in compacting the soil decreases. The USCS considers the presence of 12 percent fines as the limiting point for using the vibratory compaction method. However, a comprehensive study by Townsend[34] has shown that vibratory compaction can be used for sand containing as much as 20 percent fines. Accordingly, gravel and sand that contain fines may be described as follows:

Description	Percent Fines
Clean	0 to 5
With some fines	5 to 20
With fines	20 to 50
Fines	>50

Letter symbols

39. Letter symbols describing the coarse-size material, or that retained on the No. 200 (75-μm) sieve, are as follows:

Symbol	Description
G	More than 50 percent by weight is of gravel size (retained on No. 10 (2.00-mm) sieve)
S	More than 50 percent by weight is of sand size (passing No. 10 (2.00-mm) sieve)
W	Well graded

(Continued)

Symbol	Description
P	Poorly graded
P_n	Poorly graded with narrow gradation (i.e. uniform grading)
P_g	Poorly graded with gap gradation

40. Letter symbols describing the Atterberg fraction, or that material passing the No. 40 (425-μm) sieve are as follows:

Symbol	Description
C	Material falling above the "A" line on the plasticity chart (C clays)
M	Material falling below the "A" line on the plasticity chart (M clays)
N	Nonplastic, with LL less than 20
F	Plastic, with LL more than 20

The subdivisions of the plastic (F) fraction (i.e., L, I, H, V, E) have been defined previously.

Descriptions of Coarse-Grained Soil Groups

41. Descriptions of the coarse-grained soil groups are based on the gradation of the coarse grains as well as the characteristics of the fines present. Other supplementary descriptions are useful and necessary for both field investigations and laboratory examination. The classification and the associated group symbols are presented in a form of a grading triangle in Figure 13.

Clean coarse-grained material.

42. Clean coarse-grained material consists of gravel- and sand-size soils with less than 5 percent fines. The presence of the fine material should neither change the strength properties of the coarse material nor interfere with its drainage characteristics. For these soil groups, gradation is probably the most important factor in dictating their engineering properties, and this factor is reflected in the classification. For well graded material, the symbols GW and SW are

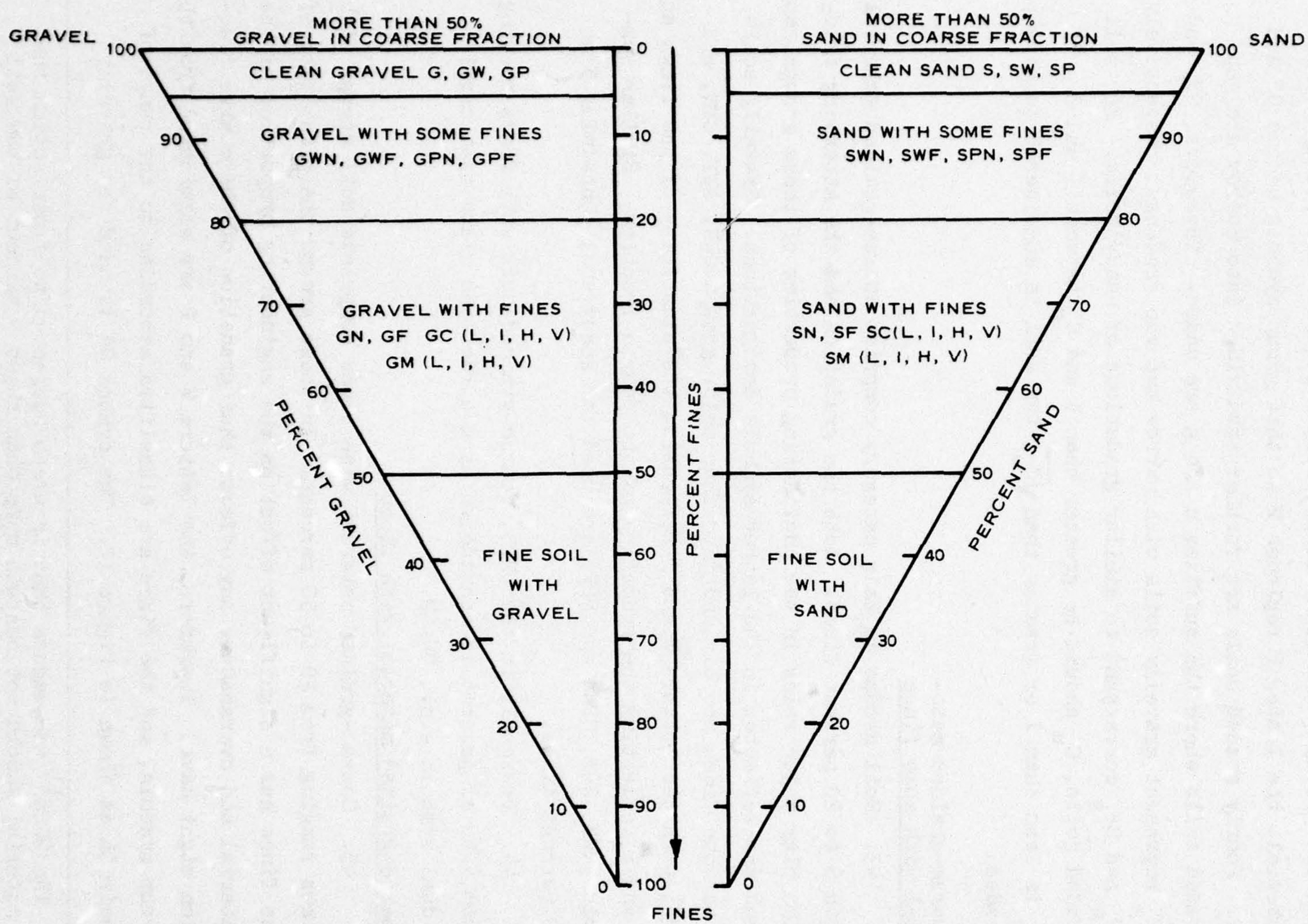


Figure 13. Grading triangle for coarse-grained soil groups

used for gravelly and sandy soils, respectively.* For poorly graded material, the letter P replaces W so that group symbols become GP and SP. Poorly graded soils are further subdivided into narrow and gap graded soils where the suffixes n and g are added. Therefore, GP_n and GP_g represent gravelly soils with narrow and gap gradings, respectively; SP_n and SP_g correspond to similar gradations of sandy soils. For well graded soils, C_u should be greater than 5 and C_c between 1 and 3. If C_c is less than 1 or greater than $\sqrt{C_u}$, the soil is considered to be gap graded.

Coarse-grained material with some fines

43. Soil groups in this category comprise coarse-grained material with 5 to 20 percent fines. Both the gradation and the Atterberg fraction play major roles in the engineering properties of these groups, and thus are reflected in the letter symbols designations. Gravelly soils with some fines are divided into four major groups GWN, GWF, GPN, and GPF, with the letters N and F reflecting the plasticity of the fines and W and P reflecting the gradation of the coarse fraction. Similar symbols (SWN, SWF, SPN, and SPF) are used for sandy soil containing 5 to 20 percent fines.

44. Presently in the USCS, coarse-grained soil with fines ranging from 5 to 12 percent is considered as a borderline class that carries a dual symbol; e.g., GW-GM.

Coarse-grained material with fines

45. Coarse-grained material with fines comprises soil groups with fines ranging from 20 to 50 percent. In these groups the plasticity of the fines has a significant effect on the engineering properties of the material and overshadows any effects that gradation of the coarse fraction might have. Therefore, the letters W and P are eliminated from the group symbols, and the fines are classified according to the range of their LL as shown in Figure 12. The symbol GN is used for gravelly

* The USCS[11] recommends that in areas subjected to frost action the material should not contain more than about 3 percent of the soil grains smaller than 2 μm in size.

soil with nonplastic fines (i.e., LL less than 20 percent), and GF is used for those with plastic fines. For detailed classification, the GF group may be divided to GM (L, I, H, V) if the Atterberg fraction plots below the "A" line on the plasticity chart and GC (L, I, H, V) if it plots above the "A" line. The same type of subdivision can be used for sandy soil with fines by substituting the letter S for G followed by the classification of the Atterberg fraction; i.e., SN, SF, SM (L, I, H, V), and SC (L, I, H, V). Figures 14 and 15 show the classification schemes for gravelly and sandy soils, respectively.

Soil Groups Pertaining to Roads and Airfields

46. Proper design of roads and airfield pavements requires detailed soil properties which cannot possibly be obtained from a general soil classification system. However, a general indication of probable soil behavior in road and airfield construction can be obtained from proper soil classification.

47. With respect to roads and airfields, the basic soil groups GM (Figure 14) and SM (Figure 15) have been each subdivided into two groups designated by the suffixes d for desirable and u for undesirable in a manner similar to that used in the USCS.[11] The soil groups GM and SM are considered desirable when the LL and PI of the Atterberg fraction are equal to or less than 25 and 5, respectively; otherwise, the GM and SM groups are considered undesirable for construction. The detailed indication of the suitability of soil groups for use as subgrade, subbase, or base material is presented in Appendix B of the USCS,[11] and only a summary of their desirability is presented here.

	Desirability As		
Soil Group	Subgrade	Subbase	Base
GW	Excellent	Excellent	Good
GP	Good	Good	Fair
GM_d	Good	Good	Fair
GM_u	Good	Fair	Poor

(Continued)

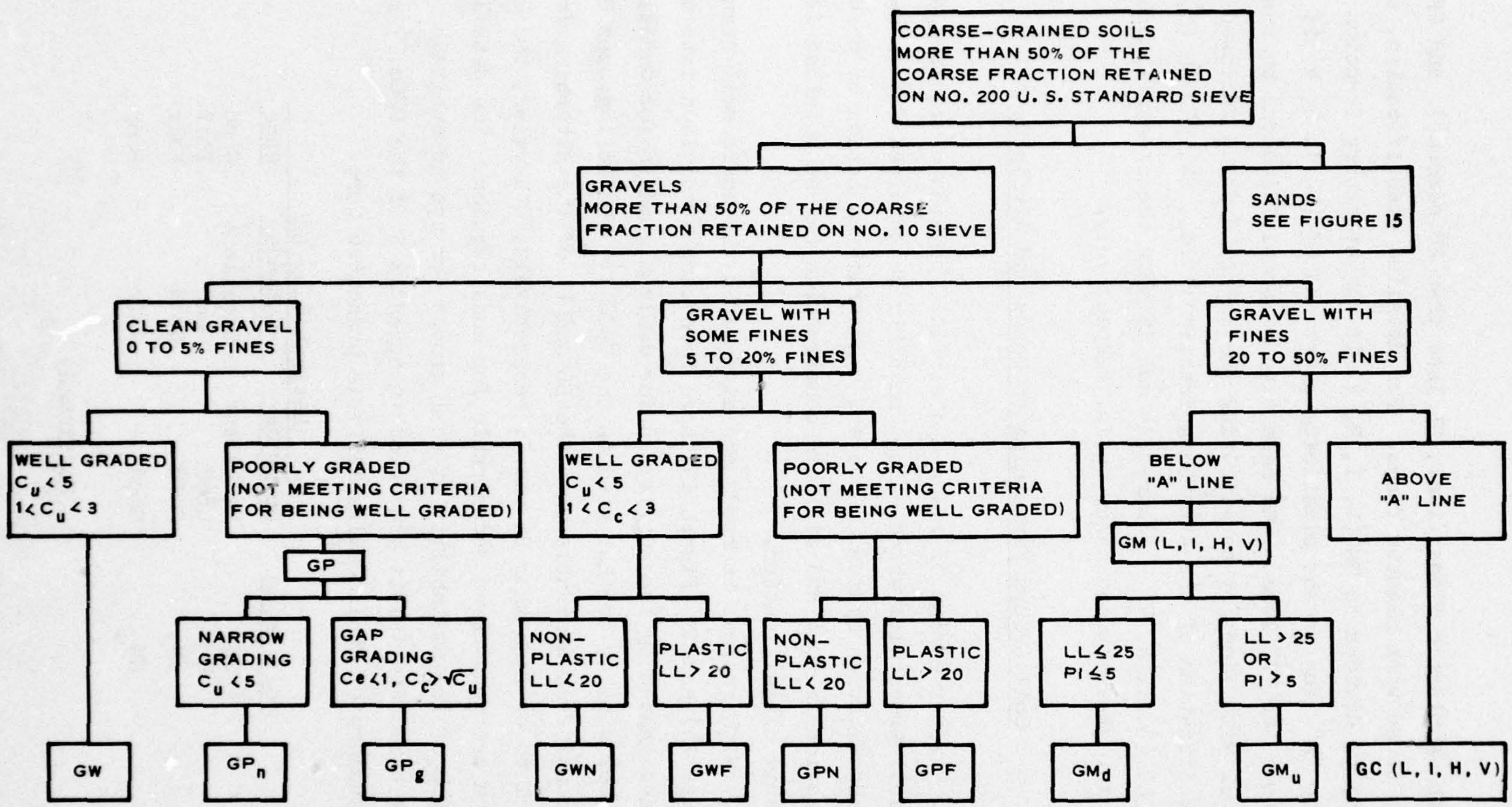


Figure 14. Classification scheme for gravelly soils

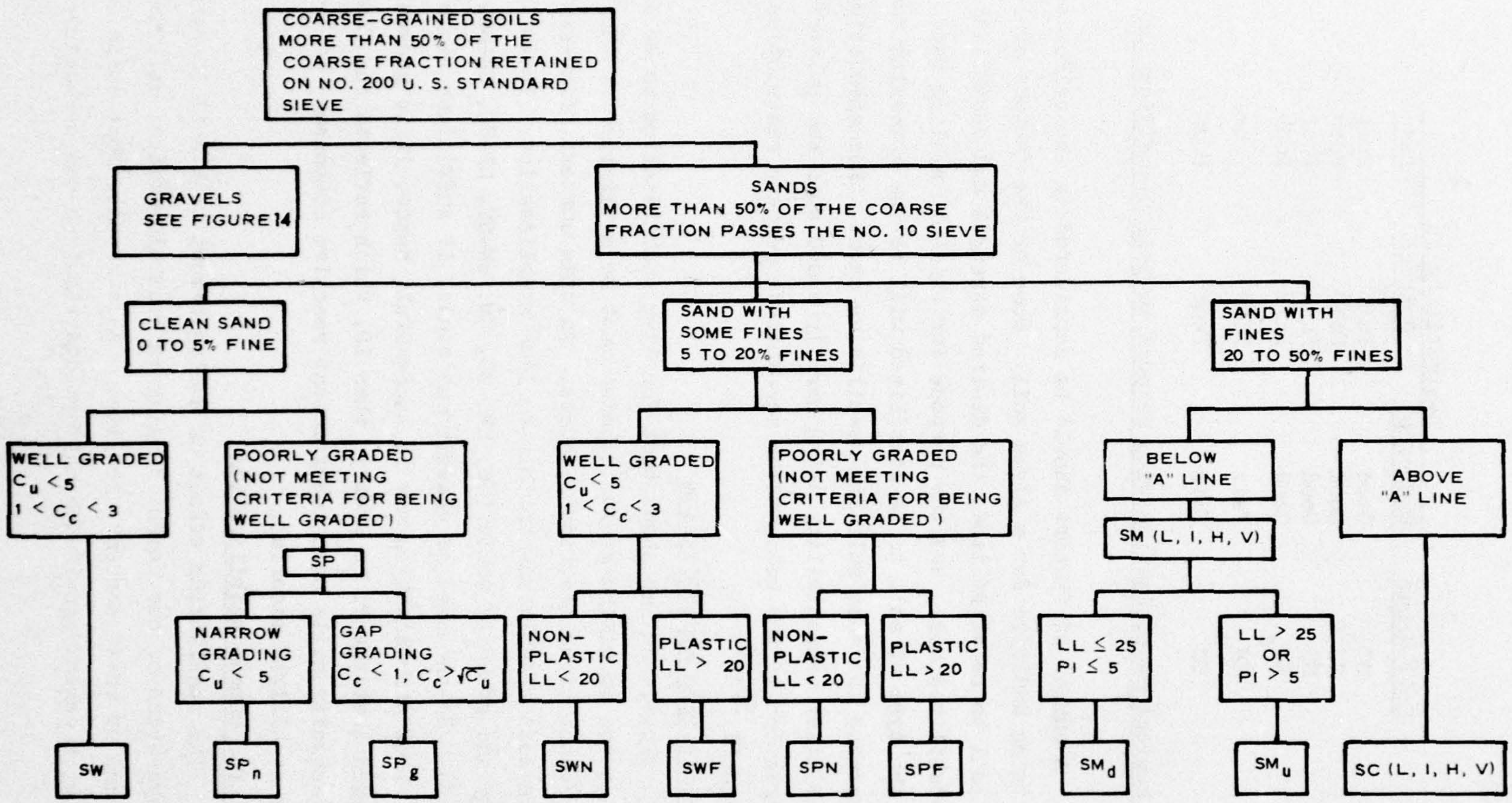


Figure 15. Classification scheme for sandy soils

Soil Group	Desirability As Subgrade	Subbase	Base
GC	Good	Fair	Poor
SW	Good	Fair	Poor
SP	Good	Fair	Poor
SM_d	Good	Fair	Poor
SM_u	Fair	Fair	Poor
SC	Fair	Poor	Poor

Chemical Stabilization with Respect to Soil Classification

48. A number of factors should be considered in the selection of a stabilizing additive for a given soil. Some of the factors are: the type of soil to be stabilized, the desired strength and durability, cost of the stabilized soil, and the purpose for which it will be used. Generally, the type of soil to be stabilized will be the governing factor in determining the most suitable stabilizing agent. Recommendations for soil-stabilizer compatibility are generally based upon the pulverization characteristics of the soil, which necessitate certain restrictions in the LL and PI.[35,36]

Criteria for lime stabilization

49. Experience has shown that for lime stabilization to be effective, a source of silica and/or alumina must be available for the formation of cementitious reaction products. In this context, fine-grained soils are most readily susceptible to lime stabilization. These include all sandy and gravelly soils (SC, SM, GC, GM, SW-SC, SP-SC, SM-SC, GW-GC, and GP-GC). In the case of gravels and sands, if sufficient fines are present, lime stabilization may be successful; hence, it is generally recommended that the PI be greater than 10, which reflects the fact that lower plasticity soils have insufficient reactive components to produce suitable stabilized material.

Criteria for cement stabilization

50. The stabilizing effect of adding cement to a soil is primarily due to hydration of the cement forming calcium aluminates, calcium silicates, and up to 20 percent free lime. As a result, most soils can be treated with cement provided a uniform distribution can be achieved.

In fine-grained soils, the lime from the cement reacts with the soil as described previously, while for coarse-grained soils, the cement "spot welds" the particles at points of contact. However, the Portland Cement Association[37] recommends that well graded granular materials (as shown below) which provide a floating aggregate mix will produce the best stabilized mixtures.

Minimum Percent Passing	Sieve
55	No. 4 (4.75 mm)
37	No. 10 (2.00 mm)
25	No. 10 (2.00 mm) to No. 200 (75 μm)

Generally, a maximum PI of 30 is specified to insure a proper mixing of the stabilizer.[36]

Criteria for bituminous stabilization

51. The mechanism by which bituminous materials provide stabilization is primarily mechanical: the bitumen provides improved stability through cementing and/or waterproofing. Generally, there are four classes of bituminous-stabilized materials: soil-bitumen, sand-bitumen, sand-gravel-bitumen, and aggregate-bitumen.

52. Soil-bitumen is a cohesive soil made waterproof, which prevents significant changes in moisture content and hence helps to maintain the natural stability of the compacted mixture. However, experience has shown that if enough plastic fines are present, the intimate mixing of the bitumen and soil required for successful stabilization is practically impossible. Hence, restrictions of PI less than 10 and less than 25 percent passing the No. 200 (75-μm) sieve are specified.[36]

53. Sand-bitumen, sand-gravel-bitumen, and aggregate-bitumen mixtures are materials which inherently possess high strength in a confined state. However, if used under conditions of low confining stresses (i.e., low strengths), the addition of bitumen can provide increased cohesion and a substantial stabilizing effect. The function of the bitumen is to provide a matrix since as the gradation is improved the contact area also increases, and this change leads to a more stable mix.

For this reason, only well graded gravels are generally recommended for bituminous stabilization.[38]

54. These recommendations for stabilizing agent selection can be grouped according to the proposed classification system as follows:[36]

Stabilizer	Soil Type*	Restriction: Atterberg Fraction	Restriction: Percent Fines
Lime	Fine-grained soil with sand or gravel**		
	SC or GS (I, H, V)	PI > 10	> 25
	GM_u or SM_u	PI > 10	> 25
	GWF, GPF, SWF, SPF		
	GWN, GPN, SWN, SPN	PI > 10	
Cement	SW, SP		
	GW, GP†		
	SWN, SPN, GWN, GPN†		
	SM_d, GM_d†		
	SM_u, GM_u†	PI < 30	
	SC, GC†	PI < 30	
	Fine-grained soil with sand or gravel**,††	PI < 30	
Bitumen	SW, GW, SP, GP	PI < 10	
	SWN, GWN, SPN, GPN	PI < 10	
	SWF, GWF, SPF, GPF	PI < 10	

* Order of listing indicates approximate order of susceptibility to stabilization by the particular agent.

** Organic and strongly acidic soils are not susceptible to stabilization by ordinary means.

† Materials containing at least 45 percent material by weight passing the No. 4 (4.75-mm) sieve are recommended.

†† LL less than 40 is recommended.

Laboratory Identification and Classification

55. Laboratory identification and classification of soils are conducted on the portion that passes the No. 4 (4.75-mm) sieve; however, the percent of the portion retained on the No. 4 (4.75-mm) sieve should be recorded. The classification procedure is centered around the gradation and the plastic properties of the materials. The gradation is determined by the standard sieve analysis method[32] where the results are plotted as percent finer by weight against the logarithm scale of grain size in millimetres. The plastic properties are determined by conducting the standard Atterberg limits tests[32] on the Atterberg fraction (i.e., the fraction finer than the No. 40 (425-μm) sieve) and comparing the results with Figure 12. The percent fines present in the coarse fraction should be noted. Figures 14 and 15 provide adequate guidance for soil classification.

Supplementary Soil Descriptions

56. In addition to the formal laboratory procedure to provide names and group symbols, there are other characteristics of soils which are important for problems dealing with field investigations or analysis and design. For coarse-grained soil, such characteristics as particle shape (see Appendix A), surface texture, color, mineralogical composition, etc., are very important features that convey additional information about probable engineering behavior. The site description can also provide additional and pertinent information on soil classification. The field description should include the density, drainage conditions, cementation and binders, stratification, etc., and should supplement laboratory soil classification data. Some recommendations with regard to soil description are provided by ASTM Designation D 2488-69.[39]

PART V: CONCLUSIONS

Conclusions

57. This report examines current systems used in classifying cohesionless soils and suggests some additions to the USCS for embankments as well as pavements. Distinctions were drawn between soil groups which have different engineering properties but are not fully described in the USCS. The following criteria are proposed as the basis for expanding and improving the USCS:

a. Soils should be classified according to the presence of fines as:

 (1) Clean gravels or sands. Fine content from 0 to 5 percent.

 (2) Gravels or sands. Fine content from 5 to 20 percent.

 (3) Gravels or sands with fines. Fine content from 20 to 50 percent.

b. Coarse-grained soils should be classified by their coefficient of uniformity (C_u) and coefficient of curvature (C_c) as:

 (1) Well graded. When C_u is greater than 5 and C_c is greater than 1 but less than 3.

 (2) Narrowly or uniformly graded. When C_u is less than 5.

 (3) Gap graded. When C_c is less than 1 or greater than $\sqrt{C_u}$.

c. The Atterberg fractions should be classified according to to the range of their LL's as:

 (1) Low. $20 < LL < 35$.

 (2) Intermediate. $35 < LL < 50$.

 (3) High. $50 < LL < 65$.

 (4) Very high. $65 < LL < 80$.

 (5) Extremely high. $LL > 80$.

d. The No. 10 (2.00-mm) sieve should be used as the dividing boundary between gravel- and sand-size particles to be in better agreement with other soil classification systems in the U. S. and abroad.

Recommendations

58. It is recommended that systematic laboratory tests be conducted on different soils to supplement and enhance the suggested additions to the USCS.

REFERENCES

1. Atterberg, A., "Die Rationelle Klassifikation der Sande und Kiese," Chemiker-Zeitung, No. 15, 1905.

2. ________, "Internationale Mitteilungen für Bodenkunde," International Committee for Mechanical and Physical Soil Investigation, October 31, 1913, Vol IV, No. 1, 1914.

3. Kopecky, J., "Ein Beitrag zur Frage der neuen Einteilung der Körungsgruppen," Internationale Mitteilungen für Bodenkunde, Vol IV, No. 2/3, 1914.

4. Goldbeck, A. T. and Jackson, F. R., "Tests for Subgrade Soils," Public Roads, Vol 4, No. 3, 1921, pp 15-21.

5. Terzaghi, K., "Erdbaumechanik auf bodenphysikalischer Grundlage," Frauz Deuticke, Leipzig und Wien, 1925.

6. Glossop, R. and Skempton, A. W., "Particle-Size in Silts and Sands," Journal, Institution of Civil Engineers, No. 2, 1945, p 84.

7. Gilboy, G., "Notes on Soil Mechanics," 1930, Massachusetts Institute of Technology, Boston, Mass.

8. "Standard Methods of Mechanical Analysis of Soils," Designate T-88-49, 1950, American Association of State Highway Officials.

9. "Progress Report of the Committee on Significance of Tests for Highway Materials of the Highway Division," Journal, Highway Division, American Society of Civil Engineers, Paper 1385, Vol 83, No. HW4, 1957, pp 1-37.

10. American Society for Testing and Materials, "Tentative Methods for Grain-Size Analysis of Soils," Designation: D 422-54T, 1958 Annual Book of ASTM Methods, 1958.

11. "The Unified Soil Classification System," Technical Memorandum No. 3-357, 1960, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

12. Federal Aviation Administration, "Airport Paving," AC 150/5320-CH, 1967, U. S. Department of Transportation, Washington, D. C.

13. Morgan, E., "An Outline of Particle Size Analysis and Some of Its Uses," Journal, Institution of Municipal Engineers, Vol 80, 1954, p 329.

14. "Standard Methods of Mechanical Analysis of Soils," Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part 2, Method T-42, 1937, p 188.

15. American Society for Testing and Materials, "Standard Methods for Grain-Size Analysis of Soils," Designation: D 422-39, 1944 Annual Book of ASTM Methods, 1944.

16. Casagrande, A., "Classification and Identification of Soils," Transactions, American Society of Civil Engineers, Vol 113, 1948, pp 901-927.

17. "The Unified Soil Classification System," Technical Memorandum No. 3-357, 1953, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

18. British Standards Institution, "British Standard Code of Practice," CP 2001 (1957) Site Investigation, London, 1957.

19. Association Swiss De Normalisation, "Soil Classification," SNV 70005 and SNV 70008, Zurich, 1959.

20. Schon, C., "Geotechnical Classification of Soil Based on USCS Classification," Bulletin de Liaison des Laboratoires des Ponts et Chaussees, No. 16, 1965.

21. Grasshoff, H., Siedek, P., and Kubler, G., Erd-Und Grundbau, 3 Vols, Werner-Verlag, Dusseldorf, 1967.

22. Archer, A. A., "Standardization of the Size Classification of Naturally Occurring Particles," Geotechnique, Vol XX, No. 1, 1970, p 103.

23. Ueshita, K. and Nonogaki, K., "On the Unified Soil Classification of Coarse-Grained Soils," No. 194, Oct 1971, Nagoya University.

24. Committee on Soil Properties of the Soil Mechanics and Foundations Division, "Standardization of Particle-Size Ranges," Journal, Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 95, No. SM5, 1969, pp 1247-1252.

25. "Report of Committee on Classification of Materials for Subgrades and Granular Type Roads," Proceedings, Highway Research Board, Vol 25, 1945, pp 375-392.

26. Klohn, E. J. and Hughes, G. T., "Buckling of Long Unsupported Timber Piles," Journal, Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 90, No. SM6, 1964, pp 107-123.

27. Seed, H. B., Woodward, R. J., and Lundgren, R., "Fundamental Aspects of the Atterberg Limits," Journal, Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 90, No. SM6, 1964, pp 75-105.

28. Shurig, D. G. and Hittle, J. E., "Field Identification of Soils and Aggregates for County Roads," County Highway Series No. 13, 1971, Purdue University, Lafayette, Ind.

29. Liu, T. K., "A Review of Engineering Soil Classification Systems," Classification, Safety Factor, Terrain, and Bearing, pp 1-22, 1967, Highway Research Board.

30. Dumbleton, M. J., "The Classification and Description of Soils for Engineering Purposes," Road Research Laboratory Report RRL 182, 1968, Crowthorne Ministry of Transportation, England.

31. Veshita, K. and Nonogaki, K., "Classification of Coarse Soil Based

on Engineering Properties," Japanese Society of Soils Mechanics and Foundation Engineering, Vol XI, No. 3, 1971, pp 91-111.

32. Office, Chief of Engineers, Department of the Army, "Engineering and Design: Laboratory Soils Testing," Engineer Manual EM 1110-2-1906, 1970, Washington, D. C.

33. Skempton, A. W., "Notes on the Compressibility of Clays," Quarterly Journal of Geologic Society, London, Vol 100, C, Jul 1944, pp 119-135.

34. Townsend, F. C., "Comparisons of Vibrated Density and Standard Compaction Tests on Sands with Varying Amounts of Fines," American Society for Testing and Materials, Special Technical Publication 523, 1972, pp 348-363.

35. Office, Chief of Engineers, Department of the Army, "Soil Stabilization for Roads and Streets," Army Field Manual 88-7, Technical Manual TM 5-888-4, 1969, Washington, D. C.

36. Dunlap et al., "USAF Soil Stabilization Index System--A Validation," AFWL TR-73-150, Jan 1974, Air Force Weapons Laboratory, College Station, Tex.

37. Portland Cement Association, "Lab Studies Set Coarse Gradation in Limits for Soil-Cement," Soil Cement News, No. 84, Jan 1966, pp 11-14.

38. Office, Chief of Engineers, Department of the Army, "Soil Stabilization Engineering Construction," Air Force Manual 88-40, Chapter 30, Technical Manual 5-887-5, May 1966, Washington, D. C.

39. American Society for Testing and Materials, "Description of Soils (Visual-Manual Procedure)," Designation: D 2488-69, 1974 Annual Book of ASTM Methods, Part 19, 1974, p 310.

40. Al-Hussaini, M., "Investigation of Plane Strain Shear Testing," Technical Report S-71-2, Report 3, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Sep 1972.

41. Wadell, H., "Volume, Shape, and Roundness of Rock Particles," Journal of Geology, Vol 40, 1932, pp 443-451.

42. Wadell, H., "Sphericity and Roundness of Rock Particles," Journal of Geology, Vol 41, 1933, pp 310-331.

43. Zingg, T., "Beitrag zur Schotteranalyse," Schweizesische Mineralogische und Petrographische Mitteilungen, Federal Institute of Technology, Band 15, 1935, pp 39-140.

44. Rittenhouse, G., "A Visual Method of Estimating Two-Dimensional Sphericity," Journal of Sedimentary Petrology, Vol 13, 1943, pp 79-81.

45. Krumbein, W. C. and Sloss, L. L., Stratigraphy and Sedimentation, 2d ed, W. H. Freeman and Co., San Francisco, 1963.

46. Krumbein, W. C., "Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," Journal of Sedimentary Particles, Vol 11, No. 2, 1941, pp 64-72.

47. Rosenfeld, M. A. and Griffiths, J. C., "An Experimental Test of Visual Comparison Technique in Estimating Two-Dimensional Sphericity and Roundness of Quartz Grains," American Journal of Science, Vol 251, 1953, pp 553-585.

48. Zelasko, J. S., An Investigation of the Influence of Particle Size, Size Gradation, and Particle Shape on the Shear Strength and Packing Behavior of Quartziferous Sands, Ph. D. Thesis, Northwestern University, Evanston, Ill., 1966.

APPENDIX A: GEOMETRIC CLASSIFICATION OF GRANULAR SOILS

1. Previous experimental work has demonstrated that the strength and compressibility of a soil mass are significantly influenced by the geometric characteristics of individual soil particles. A survey by Al-Hussaini[40]* indicates that, in general, the angle of internal friction and compressibility of granular soils increase with increasing angularity and surface roughness. Particle shape and surface roughness have an important environmental significance with regard not only to stability of earth masses but also to embankment erosion and stream sedimentation. Therefore, a relatively simple method for obtaining a geometric description of soil particles is needed if full use in engineering practice is to be made of this knowledge of geometric effects.

Sphericity

2. Description of the geometric characteristics of a particle involves several separate but related geometric concepts, the most important of which are sphericity and roundness. The true sphericity was first defined by Wadell[41] as

$$\text{True sphericity} = \frac{\text{surface area of the particle}}{\text{surface area of sphere of same volume}} \qquad \text{(A1)}$$

Measurement of the true sphericity of an irregular particle is tedious and not feasible for routine testing. In 1933, Wadell[42] proposed a practical definition for sphericity which he called "operational sphericity"

$$\text{Operational sphericity} = \sqrt[3]{\frac{\text{volume of particle}}{\text{volume of the circumscribed sphere}}} \qquad \text{(A2)}$$

In this definition, the volume of the particle may be measured by water displacement and expressed as $\pi a^3/6$. Consequently, the operational

---

* Raised numbers refer to similarly numbered entries in the References on page 46.

sphericity can be expressed as

$$\text{Operational sphericity} = \frac{d}{a} \quad \text{(A3)}$$

where d is the nominal particle diameter and a is the maximum particle diameter. For the scale of simplicity, the operational sphericity will be called "sphericity."

3. In 1935, Zingg[43] suggested that most granular particles have three distinct dimensions, with a being the maximum, b the intermediate, and c the minimum. Zingg showed that if the ratio b/a is plotted against the ratio c/b, the particles may be classified according to their shapes as indicated in Figure A1. The fact that curves of equal sphericity in Figure A1 swing across the chart indicates that

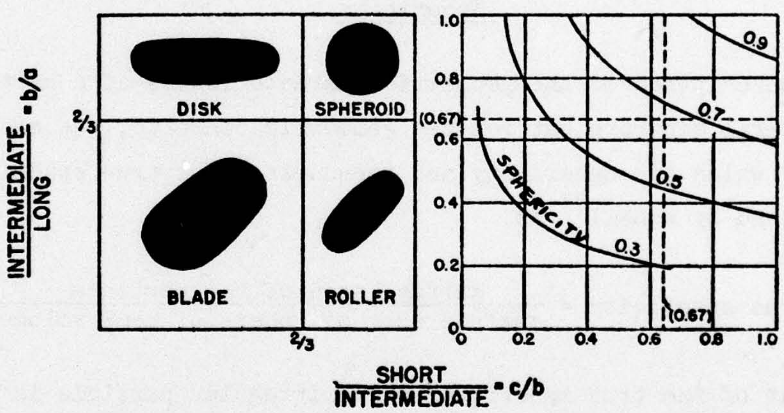


Figure A1. Zingg[43] classification of grain shapes based on the ratio of their dimensions

particles with different geometrical appearances may have the same numerical value of sphericity. It might be appropriate to call disk-shaped particles which have a tendency to split "flaky" and particle shapes which do not conform to any of the shapes suggested in Figure A1 "irregular." The ratio of surface area to volume is of course less for a sphere than for any other geometrical shape. Consequently, as the shape of a particle departs from a spherical shape (i.e., decreases in sphericity), the resistance of the particle to movement by external forces may increase while its resistance to bending deformation may decrease.

Sphericity Measurements for Sand

4. The procedure previously described for measuring sphericity can be conveniently applied for gravel and larger particles which can be handled individually. For finer particles such as sand, the previous procedure may not be practical and another method may be required. One convenient method is the procedure suggested by Rittenhouse[44] which consists of placing a representative amount of sand on a transparent slide under a microscope. The sand grains are then photographed and compared with the Rittenhouse standard charts shown in Figure A2. Not less than 50 grains should be used in determining representative sphericity.

5. The sphericity data can be presented in the form of a histogram and cumulative curve, as shown in Figure A3, in a manner similar to a conventional grain-size distribution curve. A graphical procedure which yields answers very close to those from a statistical analysis can be used to determine the average sphericity of the granular material. In this procedure, the average sphericity is obtained from measurement of the median or mean sphericity as follows:

$$\text{Median sphericity} = X_{50} \tag{A4}$$

$$\text{Mean sphericity} = (X_{84} + X_{16})/2 \tag{A5}$$

$$\text{Sphericity standard deviation} = (X_{84} - X_{16})/2 \tag{A6}$$

where X represents the sphericity for the subscripted percentile on the cumulative scale (Figure A3).

Roundness

6. In 1932, Wadell[41] defined roundness as the ratio of the average radius of corners and edges to the radius of the maximum inscribed circle:

$$\text{Roundness} = \frac{\text{average radius of corners and edges}}{\text{radius of maximum inscribed circle}} \tag{A7}$$

7. The roundness of granular material, similar to its sphericity, can be obtained by spreading a small quantity of the material on a

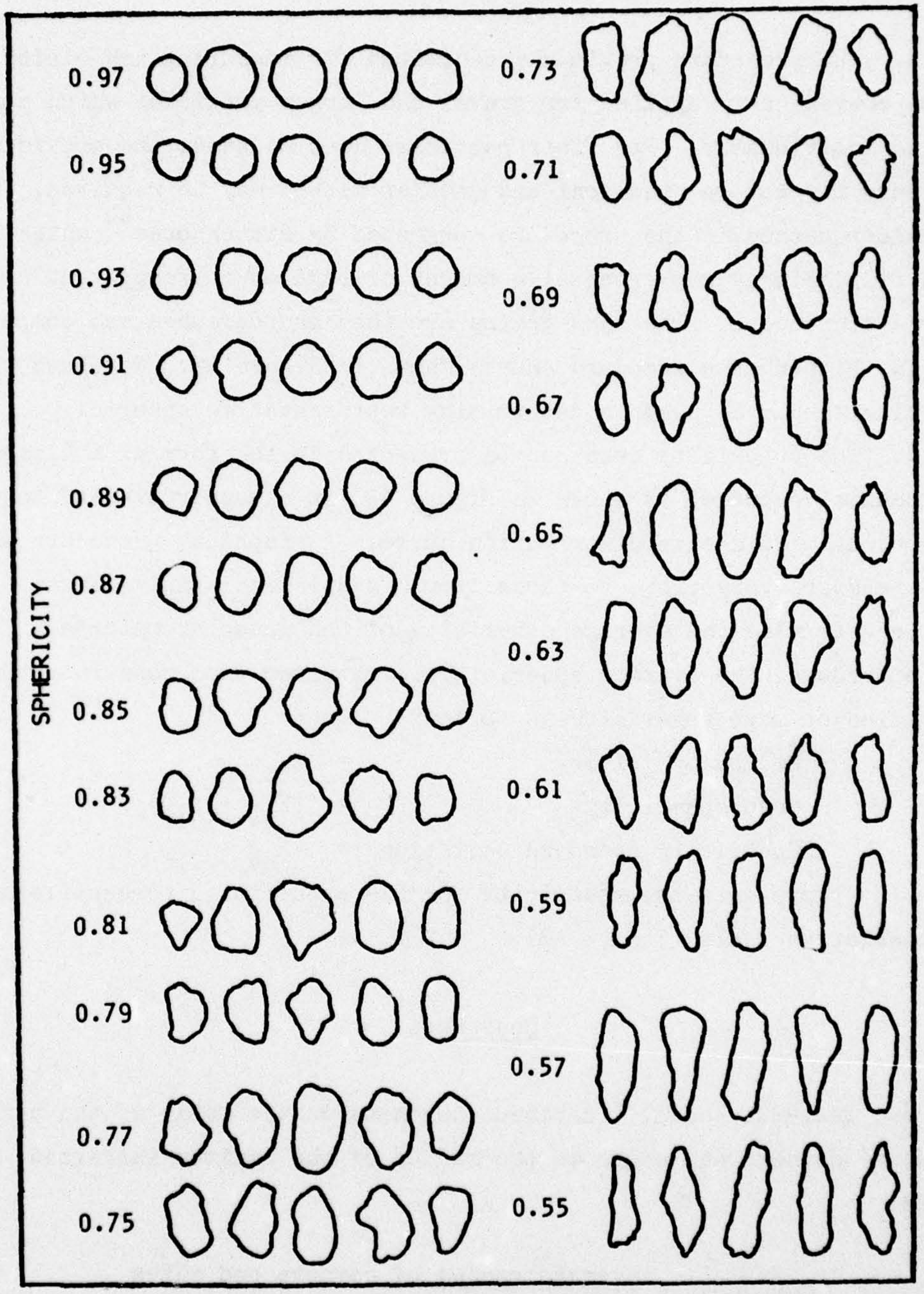


Figure A2. Rittenhouse standard chart[44] for determining visually the projection sphericity of sands and other particulate materials

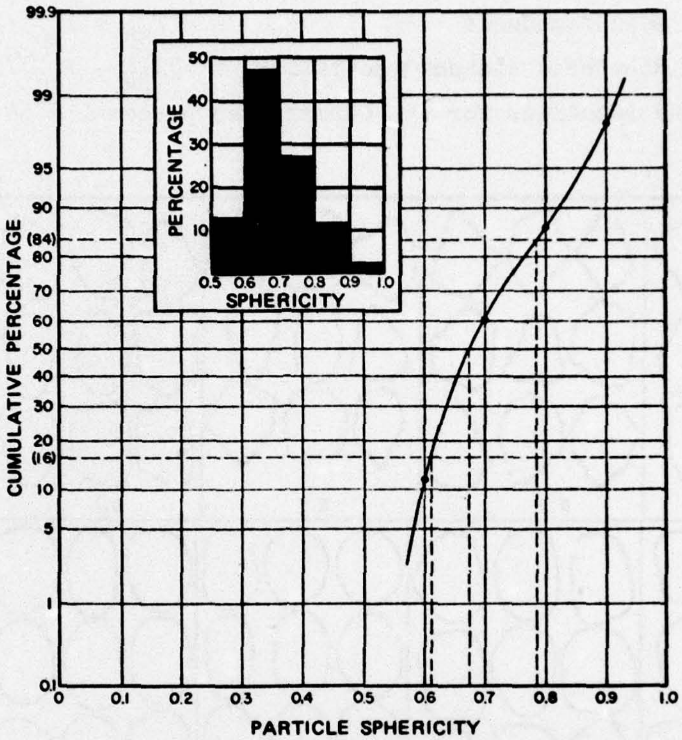


Figure A3. Histogram and cumulative curve of sphericity distribution of river pebbles. The dashed lines show the 16th, 50th, and 84th percentiles on the cumulative probability graph (after Krumbein and Sloss[45])

cover plate under the microscope or by using a photograph enlarged and traced to obtain images for measurements. A visual estimate of particle roundness can be made using the chart shown in Figure A4, which was originally prepared by Krumbein.[46] Figure A4 shows that particles of low roundness have numerous pits, ferrules, and jagged edges while particles of high roundness have relatively smooth surfaces. Wide variations in texture can also be observed among particles of the same roundness.

8. The average roundness, similar to sphericity, may be determined using the cumulative probability curve and histogram shown in Figure A5. The average roundness may be determined using the median and mean roundness as follows:

$$\text{Median roundness} = X_{50} \tag{A8}$$

$$\text{Mean roundness} = (X_{84} + X_{16})/2 \quad \text{(A9)}$$

$$\text{Roundness standard deviation} = (X_{84} - X_{16})/2 \quad \text{(A10)}$$

where X is the roundness for the subscripted percentile on the cumulative scale.

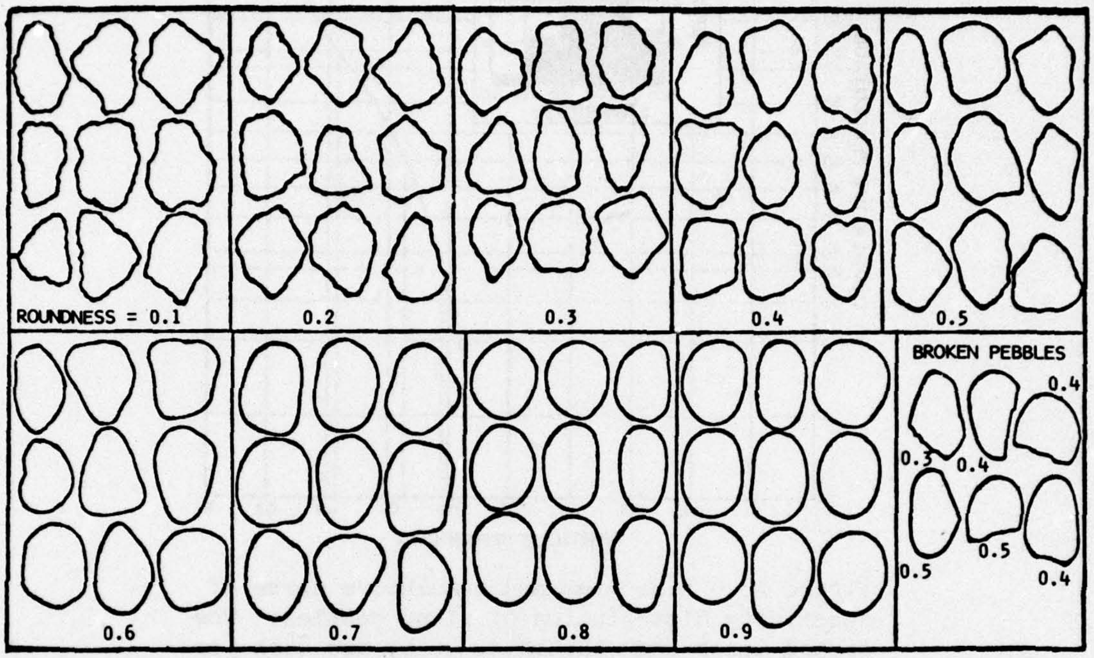


Figure A4. Krumbein standard chart[46] for determining visually the protection roundness of sands and other particulate materials

9. It should be noted that visual estimates of particle sphericity and roundness are subject to some variation among different observers. However, it has been previously documented by Rosenfield and Griffiths[47] that the average roundness based on 50 grains or more tends to be similar for the different observers because of compensating errors. Average sphericity and roundness for different granular materials are presented in Table A1.

<u>Rapid Determination of Sphericity and Roundness for Sand</u>

10. The previous procedures for determining sphericity and roundness (using Figures A2 and A4, respectively) can be applied very

Table A1

Particles Roundness and Sphericity for Different Granular Materials

Material	Average Sphericity	Average Roundness
Dune sand, recent, Cook County, Ill.*	0.75	0.70
Beach sand, recent, Cook County, Ill.*	0.83	0.64
Beach gravel, recent, N. Shore, Lake Superior*	0.64	0.61
Stream gravel, recent, Los Angeles County, Calif.*	0.71	0.34
Glacial till pebbles, Cary, Ill.*	0.72	0.54
Glacial outwash gravel, Cary, Ill.*	0.75	0.58
Francis Creek shale (Pennsylvanian), Fulton County, Ill. (silt only)*	0.80	0.30
Ottawa sand, Ottawa, Ill.**	0.87	0.65
Franklin Falls Dam sand, Mass.**	0.82	0.36
Evanston Beach sand, Evanston, Ill.**	0.81	0.44

* From Krumbein and Sloss.[45]

** From Zelasko.[48]

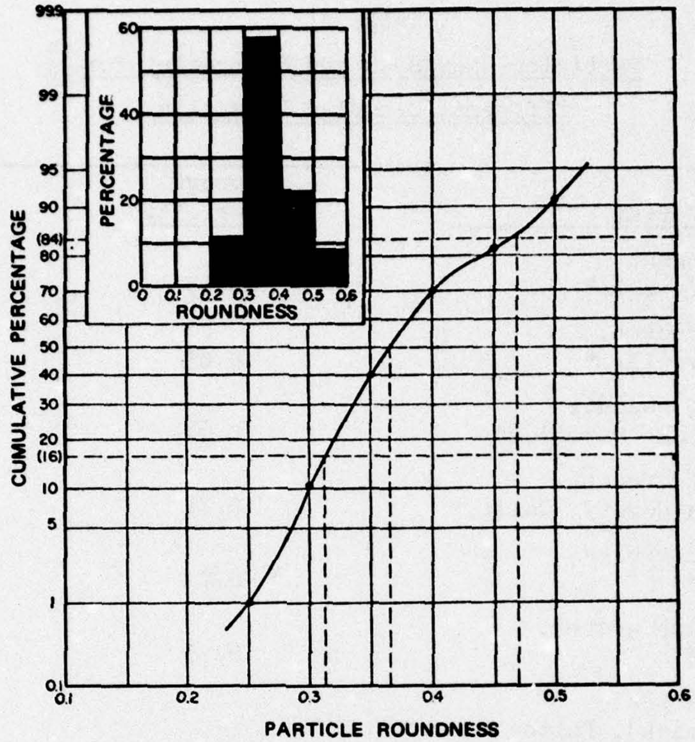


Figure A5. Histogram and cumulative curve of roundness distribution of river pebbles. The dashed lines show the 16th, 50th, and 84th percentiles on the cumulative probability graph (after Krumbein and Sloss[45])

conveniently for coarse-grained soil. However, for finer grained soils such as sand, the procedure is difficult and tedious. For rapid analysis of sand, Krumbein and Sloss[45] developed the chart shown in Figure A6, which can be used for the visual determination of sphericity and roundness simultaneously.

Descriptive Terms for Particle Shapes

11. In the classification of cohesionless soil, it is appropriate and necessary to include a description of particle geometry. The descriptive terms used should be related to numerical values that can be obtained from a well defined procedure to eliminate ambiguity and to provide a meaningful way of conveying particle descriptions accurately

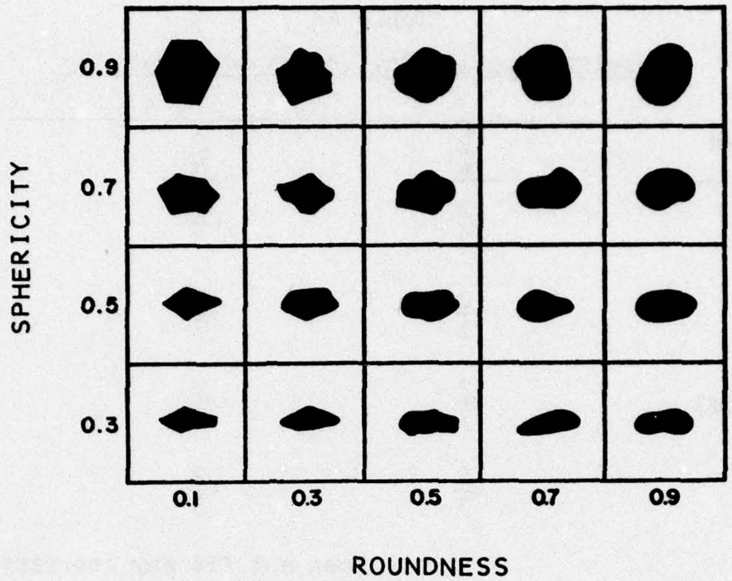


Figure A6. Krumbein and Sloss[45] standard chart for visual estimation of roundness and sphericity of sand grains

among those individuals interested. Such an objective can be easily accomplished with regard to roundness of the particle since the degree of roundness or angularity of particles can be bounded. However, because it is possible to have more than one particle shape for the same sphericity (see Figure A1), it is not possible to assign a certain limit of sphericity to define a particular geometric shape without an additional detailed analysis. The descriptive system presented in Table A2 could be used for particle sphericity. In the event that a detailed analysis is not available, descriptive terms based on visual observations by a trained technician should be sufficient. A suggested descriptive system that defines the degree of roundness or angularity is presented in Table A3. It is also possible to combine the sphericity and roundness descriptions into one table as shown in Table A4 to be used in conjunction with the soil classification system.

12. From the above discussion, it should be evident that particle geometry, which significantly influences soil properties, can be defined by a simple and reproducible procedure that satisfactorily describes particle shape. However, the characterization of particle shape can

Table A2

Classification of Soil Based on Sphericity

Descriptive Term	$\frac{b}{a}$	$\frac{c}{b}$	Sphericity Range
Sphere	$>\frac{2}{3}$	$>\frac{2}{3}$	1.0 to 0.7
Disk	$>\frac{2}{3}$	$<\frac{2}{3}$	0.8 to 0.3
Eliptic (rod)	$<\frac{2}{3}$	$>\frac{2}{3}$	0.7 to 0.2
Blade	$<\frac{2}{3}$	$<\frac{2}{3}$	≤ 0.6
Irregular	Does not fit any description		

Table A3

Classification of Soil Based on Roundness

Descriptive Term	Roundness Range
Rounded	≥ 0.8
Subrounded	0.8 to 0.6
Subangular	0.6 to 0.4
Angular	≤ 0.4

Table A4

Descriptions of Particle Shape

Roundness	Sphericity				
	Sphere	Disk	Rod	Blade	Irregular
Rounded >0.8	rounded spherical	rounded disk	rounded rod	rounded blade	rounded irregular
Subrounded (0.8 to 0.6)	subrounded spherical	subrounded disk	subrounded rod	subrounded blade	subrounded irregular
Subangular (0.6 to 0.4)	subangular spherical	subangular disk	subangular rod	subangular blade	subangular irregular
Angular >0.4	angular spherical	angular disk	angular rod	angular blade	angular irregular

assume a useful function only when it is related to soil properties such as strength and compressibility in a manner similar in its simplicity to that used in utilizing the index properties of cohesive soil. Such correlation will require extensive experimental and analytical studies to fill this gap in the current soil classification systems.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Al-Hussaini, Mosaid M
  Contribution to the engineering soil classification of cohesionless soils / by Mosaid M. Al-Hussaini. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
  49, 12 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-77-21)
  Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Project No. 4A161102AT22.
  References: p. 46-49.

1. Cohesionless soils. 2. Soil classification. 3. Unified Soil Classification System. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-77-21.
TA7.W34m no.S-77-21